Sedimentation and Sustainable Use of Reservoirs and River Systems

DRAFT ICOLD BULLETIN

Sedimentation Committee
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March 2009

Summary

High rates of sedimentation in many reservoirs and better care of long term sustainability have emphasized the importance of reservoir sedimentation.

The main reservoir sedimentation problems are:
- Loss of storage capacity
- Damages to turbines and loss of hydropower production
- Downstream impacts

The total world reservoir storage is about 7000 km^3 (6100 km^3 based on the ICOLD Register of Dams, but if smaller <15m dams are included, 7000 km^3 could be the current total storage), of which 3000 km^3 is dead storage for hydropower dams. From 4000 km^3 of live storage, most is devoted to hydropower and about 1000 km^3 to irrigation dams, potable or industrial water storage; part is in multipurpose dams.

The annual sediment load of all the world's rivers together is evaluated between 24 and 30 billion tons (Walling pers comm., 2008) for a water inflow of 40000 km^3, i.e. an average sediment content of 0.6 to 0.75 T/1000 m^3 of water but it varies enormously according to the river and the discharge. All rivers are not dammed and all sediments are not trapped in reservoirs: the accumulated sediment storage in world reservoirs has been evaluated as 2000 million m^3 for dams 35 years old on average, i.e. in the range of 57 billion m^3 per year, i.e. 0.8 % of the total storage per year.

Most sedimentation is at hydropower dams, partly in dead storage but the loss of power supply is however not proportional to the loss of live storage. The annual loss of power supply appears thus in the range of 0.6% of a total investment of about 1000 billion \$ for live storage, i.e. 6 billion \$ per year. As hydropower reservoirs silt up however, they have to be replaced by new dams eventually at a cost of the total storage capacity (dead and live) and at a total investment of 1700 billion \$, the annual cost of replacement is 0.8% x 1700 = 13.6 billion \$/year.

The annual loss of storage of irrigation reservoirs, possibly 10 billion m^3, impacts directly on the irrigation capacity; for an investment of 0.2 to 0.5 \$/m^3 for reservoirs in excess of 10 million m^3, or up to 1 \$/m^3 for dams smaller than 50000 m^3often found in the Indian sub continent and in Africa, with say a global investment cost of 0.5 \$/m^3 the annual loss may be in the range of 5 billion \$. There is also the cost of downstream damages and, for possibly 5 or 10% of hydropower plants, losses of power supply and cost of maintenance for turbine wear.

The total yearly loss linked with sedimentation problems is thus about 18.6 billion \$ (excluding downstream impacts) and with downstream impacts considered the annual cost is about 21 billion \$ and deserves great care. It should however be compared with the annual overall costs and benefits of dams, i.e.:
- Some 40 billion \$ (WCD stated 32 to 46 billion \$ during 1990s) of investments and 17 billion \$ for operation, maintenance and upgrading (0.7% x 2400 billion \$; rate usually 0.3 to 0.7%), i.e. a total cost in the range of 57 billion \$.
- Some 125 billion \$ electric power supply (2500 TWH x 0,05 \$) and 50 to 100 billion other benefits (especially food by irrigation for over 500 million people).

The total yearly impact of siltation of 21 billion \$ should thus be compared with the overall yearly costs (57 billion \$) and overall yearly benefits (175 to 225 billion \$) of the world's dams. The annual cost of reservoir sedimentation (in terms of replacement cost) is thus about 37 % of the overall costs, which is not

insignificant. However, much less than 37% is currently spent on sedimentation mitigation measures and the problems are therefore postponed to future generations in many countries.

A great care of siltation is justified for the following reasons:
- The costs are high and a better knowledge based upon experience of various countries favours efficient mitigation.
- Sedimentation is high in areas where most future dams will be constructed.
- Beyond economic optimization, the care of long term sustainability is a key element of future dam acceptability.

This Bulletin discusses the upstream and downstream fluvial morphological impacts of reservoir sedimentation and possible mitigation measures. The current state and possible future sediment deposition in reservoirs have been investigated globally with the aid of the ICOLD Register on Dams. The Bulletin also investigates the impacts of dams on the ecology related to fluvial morphological changes, and guidelines are proposed to try and mitigate the impacts on the downstream river morphology. Finally an economical model is presented which considers a life cycle approach and reservoir conservation.

This bulletin has been prepared by the ICOLD Committee on Reservoir Sedimentation and was edited by Prof GR Basson, chairman of the committee. A part of Chapter 5 was written by Dr J King and Dr G Annandale compiled Chapter 7. The bulletin was peer reviewed by member countries of ICOLD during 2009.

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Sedimentation and Sustainable Use of Reservoirs and River Systems

Table of Contents

List of Figures

List of Tables

1. Introduction

1.1 Background

Dams cause flood attenuation and sediment trapping. Flood attenuation has a major impact on flow variability downstream and rivers tend to narrow if major tributaries do not help to restore the flow and sediment balance downstream. Reservoir sedimentation occurs worldwide at a rate of about 0.8 percent per year, but the sedimentation rate in many regions such as Asia is much higher. Using an average rate, Palmieri (2003) estimated the loss to be approximately 45 km^3 per year. The cost of replacing the lost storage is significant; nearly US$ 13 billion per year would be needed, even without including the environmental and social costs associated with new dams (Palmieri, 2003). The average age of reservoirs is now about 30 years and since many reservoirs have been designed with a dead storage for sedimentation of about 50 years, serious sedimentation problems are going to develop with about 40 percent of the storage capacity in reservoirs affected within the next 20 years. Most of the existing reservoirs in the world could be completely silted up in 200 to 300 years from now, with large reaches of river system permanently lost. These rivers will have a flatter slope than the original natural rivers, with wide floodplains flooded regularly. The ecological functioning would be completely different and only run-of-river water diversion schemes could be implemented.

Dams are constructed for many reasons such as flood attenuation, hydropower generation, storage for irrigation, navigation, etc. When a reservoir is relatively small in relation to the mean annual runoff (MAR) (say less than 10%), and the sediment yield is relatively high, there is a high risk that it would silt up in a short period of time. The rate of sedimentation and ultimate storage capacity of small reservoirs can however be controlled by sluicing or flushing of sediment through large low level outlets during floods or the rainy season. If most existing and still to be constructed reservoirs are managed in a sustainable manner, the number of new dams required to maintain reliable water and power supply will decrease.

The historical growth in storage capacity up to 2000 and sedimentation is shown in Figure 1.1-1.

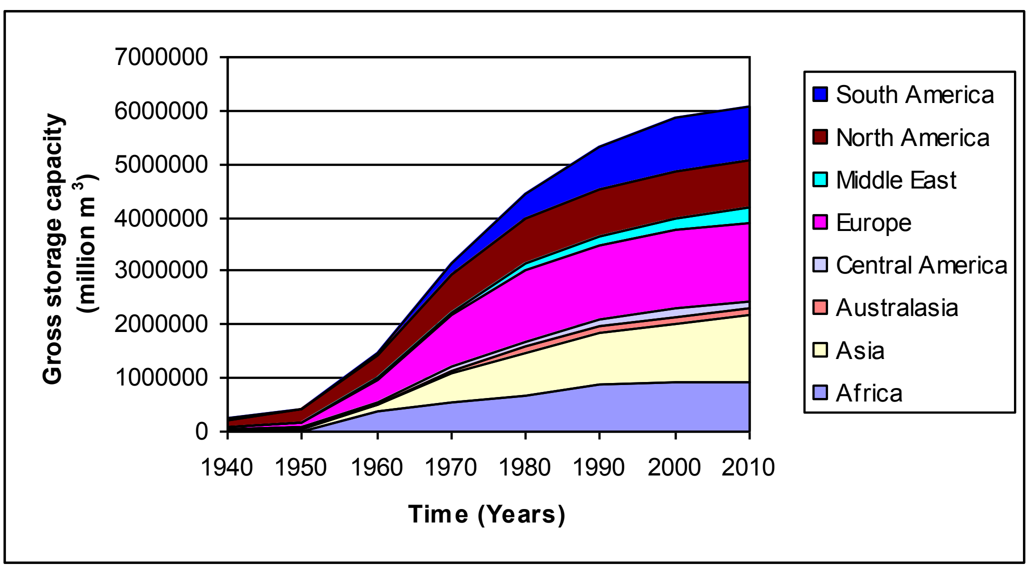


Figure 1.1-1a Historical growth in global storage capacity (Basson, 2008)

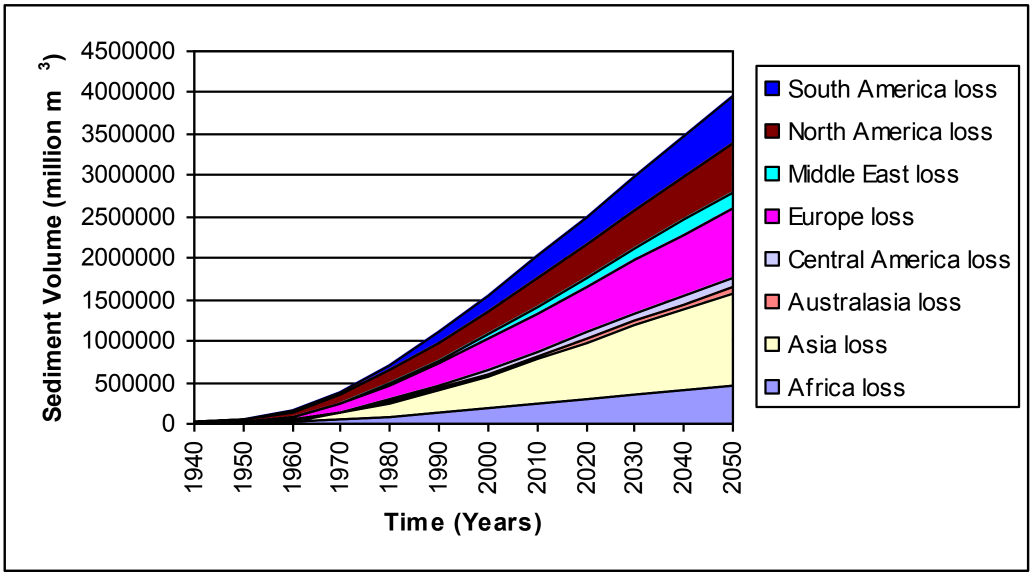


Figure 1.1-1b Historical growth in global reservoir sedimentation (Basson, 2008)

Water is the basis of life, and its proper management and conservation is essential for all socio-economic developments. It has been recognized that, due to its crosscutting nature, sustainable use of available water resources is critical to meeting the goal of eradicating poverty especially in Africa. Providing access to basic water supply and sanitation to a large number of Africa's population, contributing to food security through use of water for agriculture, and also developing the substantial untapped and renewable hydropower potential of the continent, are some of the key areas which need to be addressed if the war against poverty is to be won.

The construction of a dam can drastically alter the flow regime and sediment load of the river downstream by altering flood peaks and durations, as well as by trapping large amounts of sediment. The imposed changes in the flow can lead to riverbed degradation directly downstream, as a result of very low sediment loads, as well as narrowing of river channels due to decreased transporting capacities further downstream. The increasing number and size of dams built during recent decades has drawn more attention to the impacts that dams can have.

When attempting to analyse the impacts of dams on the downstream river morphology, there are two fundamental questions that have to be answered:

What sort of changes are to be expected, e.g. will the river become deeper or shallower and by how much?

How do these changes come about, e.g. does the river become deeper because of a lack of released sediments, or narrower due to reduced flood peaks?

In order to answer these two questions the first step has to be to determine the factors that influence the channel morphology and the aspects of the river morphology that are likely to change. A study of existing literature offers some answers in that respect since numerous studies have dealt with these aspects.

This does, however, not resolve the question of the magnitude or direction of the changes that are to be expected. What is necessary is to be able to describe the channel geometry in terms of the factors that are likely to have a significant effect. For natural rivers so-called regime equations, which were either empirically or theoretically derived, were used in the past to describe the river channel geometry. A somewhat different approach is necessary for impacted rivers.

An important aspect of all the regime equations has always been the determination of the so-called dominant or effective discharge, responsible for maintaining or forming the river channel. The determination of the dominant or effective discharge is not only important for the regime equations but also plays a vital role in determining a controlled flow regime that will maintain a river in its natural or desired state.

Once these matters have been dealt with, the second part of the problem has to be addressed. The sediment transport characteristics of the downstream river channel play a vital role in this regard. Generally speaking, degradation of the riverbed takes place close to the dam whereas further downstream aggradation is more common, since sediments are supplied by the tributaries, which cannot all be transported because of the lower sediment transport capacities due to the reduced flood peaks. The material that thus becomes deposited may consist of both coarse and fine fractions, including cohesive sediments. Fine materials, consisting of clay and silt fractions, display distinctly different erosion and deposition to non-cohesive sediments, due to the fact that the erosion resistance of fine particles is governed to a large degree by physical and chemical forces. Knowledge of the behaviour of fine sediments may also be useful for sediment flushing from reservoirs, since the reservoir deposits usually contain high percentages of clay and silt.

The materials found in the downstream river channel are not the only factors that determine why a river will change as it does. Other key factors are the flows released from the reservoir as well as the amount of sediment supplied by the downstream catchment. The regime equations mentioned above may give an indication of the magnitude and direction that changes in the river morphology may take, but they cannot describe whether a river will change in response to lower flood peaks or longer flow durations. One way in which to accurately determine the effect of a sequence of events is through numerical modelling. A model should take into consideration the effect of fine materials, changes in cross-sectional shape or slope along a river section and also the variability of flows. In this way the long-term impacts of dams can be studied and from the results assessments can be made about the required flood magnitude, duration and frequency.

1.2 Aims

The overall aim of this bulletin is to investigate the impacts of dam developments on the river morphology, specifically the assessment of the changes in the upstream and downstream river morphology as a result of different dam development scenarios.

1.3 Report structure

This report is structured as follows:

Chapter 2 discuss the state of reservoir sedimentation, while Chapter 3 discusses downstream fluvial morphological impacts of a dam. River channel morphology regime equations are derived in Chapter 4 which could be used to assess the impact of a dam on the river morphology. Chapter 5 presents ecosystem impacts caused by dams related to fluvial morphological changes, while Chapter 6 presents guidelines to limit the impact of a dam on the downstream river morphology. Chapter 7 discusses an economical model which considers reservoir conservation and a life cycle approach.

2. Upstream fluvial morphological impacts due to reservoir sedimentation

2.1 Reservoir storage capacity, operation and sedimentation

In order to understand how efficiently sediment control measures can deal with reservoir sedimentation, their respective impacts on sediment loads and on trapping of sediment need to be considered. Over the long term, a sediment load-discharge relationship as indicated in Figure 2.1-1 is obtained for a "natural" river, indicated by data points for the flood season and the low flow season (Jan to Aug).

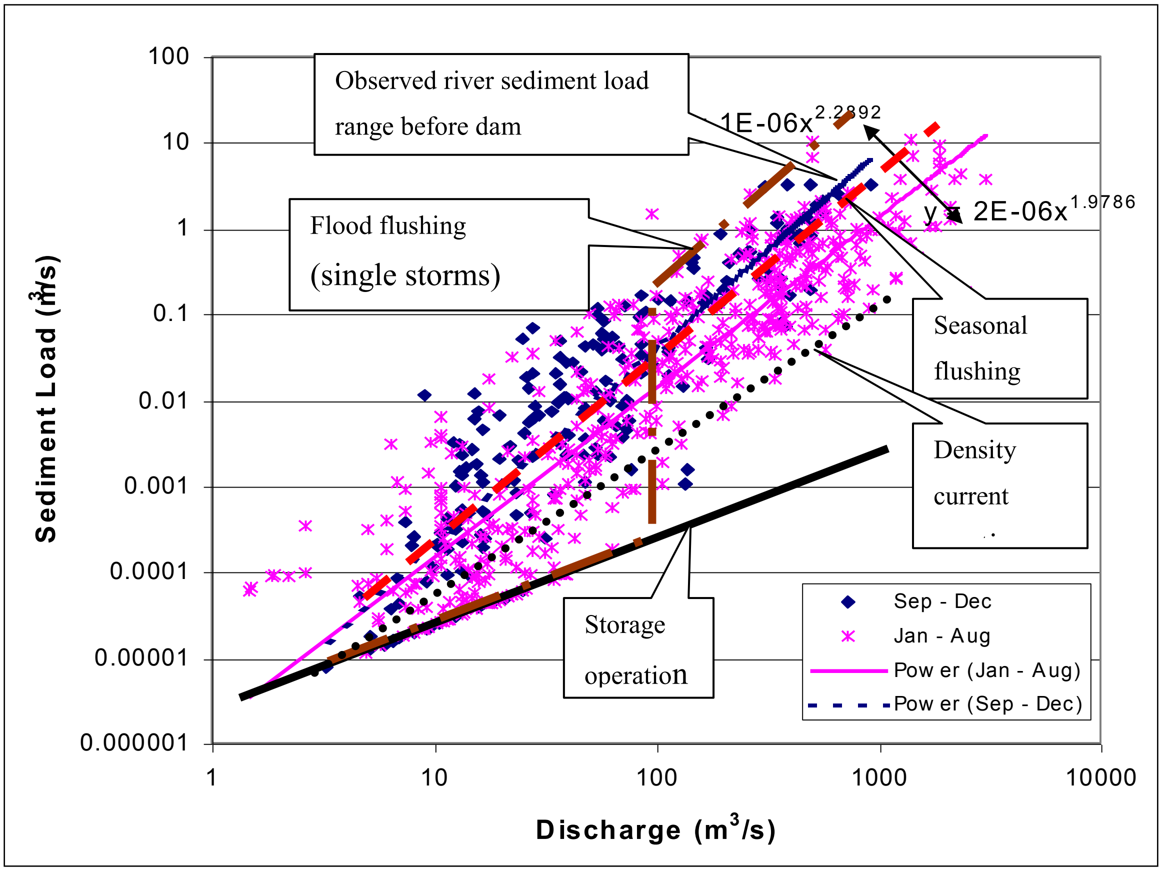


Figure 2.1-1 Reservoir operation and possible changes in the outflow sediment load-discharge relationship

One typical management option but extreme in terms of sediment transport is storage operation, allowing almost no through-flow of suspended sediment. Almost clear water will be released from storage operated reservoirs, typically resulting in channel degradation downstream of the dam. With regular flood flushing (normally practised in semi-arid regions but only when excess water is available), the operational method is only efficient above a certain discharge. At high discharges, sediment loads higher than the mean seasonal sediment observed for the pre-dam scenario can be expected, but sediment equilibrium can be established. Regular flushing with suitable bottom outlets will ensure that flushed sediment approach the mean background level of sediment concentrations as for the pre-dam conditions. Sluicing (passing through) is another method of operation (partial water level drawdown during high inflows) which can limit the outflowing sediment loads to those for typical natural conditions, but a long-term equilibrium in sediment inflow and outflow cannot be established, since low inflow conditions will normally not be sluiced especially in arid conditions in order to avoid risking failure in water supply. Under such conditions sluicing only delays the rate of reservoir sedimentation and it needs to be used in conjunction with flood flushing to maintain substantial long-term reservoir capacity.

Figure 2.1-1 shows that reservoir operation with combined sluicing and flushing operation should in the long term impact least on the sediment balance if practised regularly, coinciding with high inflow conditions. Rapid changes in water quality with low concentrations of dissolved oxygen and high suspended sediment loads during flood flushing/sluicing (uncharacteristic of the natural river) need to be considered, however, in order to protect the aquatic ecosystem downstream of the dam.

Density current venting of sediment laden flows can also limit the rate of sedimentation, but very specific boundary conditions are required and therefore the general efficiency is less than with flushing/sluicing. This is because of a number of reasons such as: only fine sediment is transported through the reservoir with coarse sediment deposition where the density current forms, as well as the judicious opening of suitable outlets to vent the density current. It also requires excess water, but its key benefit is that the reservoir water level does not have to be lowered.

For flushing/sluicing operation the major constraint is excess water availability, which means that the reservoir has to be small in relation to the runoff if the water is used consumptively. In practice, the most efficient passing through of sediment is obtained when the reservoir capacity is less than 5 % of the mean annual runoff, although larger reservoirs are also sluiced successfully. The Churchill (1948) and Brune (1953) empirical trap efficiency curves indicate why reservoirs need to be so small.

The experience gained at Sanmenxia Reservoir, China, (Delft Hydraulics, 1992) with different reservoir operating rules is further illustrated in Table 2.1-1. It was only after reconstruction of the outlets that sediment sluicing could be optimized, with much reduced operating water levels, but with the advantage of maintaining long-term reservoir capacity. Figure 2.1-2 shows Sanmenxia Dam flushing after reconstruction of the outlets.

Table 2.1-1 Reservoir operation and sediment trapping in Sanmenxia Reservoir

Period	Operation*	Maximum water level (m)	Minimum water level (m)	Sediment outflow as % inflow
9/60 – 3/62	A	332.58	324.04	6.8
4/62 – 7/66	B	325.90	312.81	58
7/66 – 6/70	C	320.13	310.00	83
7/70 – 10/73	D	313.31	298.03	105
11/73 – 10/78	D	317.18	305.60	100

Note* A: Storing water

B: Flood detention and sluicing through 2 tunnels and 4 penstocks

C: Flushing by opening 2 tunnels and 4 penstocks

D: Flushing: 2 tunnels, 4 penstocks and 8 diversion outlets

Figure 2.1-2 Sanmenxia Reservoir flushing after reconstruction of the outlets

When the storage capacity-mean annual runoff (MAR) ratios of reservoirs in the world are plotted against the capacity-sediment yield ratio, the data plot as shown in Figure 2.1-3, and with envelope lines shown in Fig 2.1-4. Most reservoirs have a capacity-MAR ratio of between 0.2 to 3, and a lifespan of 50 to 2000 years when considering reservoir sedimentation.

When the capacity-MAR ratio is less than 0.03 especially in semi-arid regions, sediment sluicing or flushing should be carried out during floods and through large bottom outlets, preferably with free outflow conditions. Flushing is a sustainable operation and a long-term equilibrium storage capacity can be reached. Seasonal flushing for say 2 months per year could be used in regions where the hydrology is less variable with capacity-MAR ratios up to 0.2. Seasonal flushing can also be practised at these relatively high capacity-MAR ratios when water demands and high sediment loads in the river are out of phase.

When capacity-MAR ratios are however larger than 0.2, not enough excess water is available for flushing and the typical operational model is storage operation. Density current venting can be practised at these reservoirs, as well as dredging to recover lost storage capacity.

The operating rules for a reservoir need not be inflexible, but can change with different stages of storage loss. Storage operation may be continued in reservoirs with large capacities relative to the sediment loads, while sluicing/flushing operation can be introduced once the loss of storage capacity reaches a certain stage. These transition zones can be found between the zones represented in Figure 2.1-4.

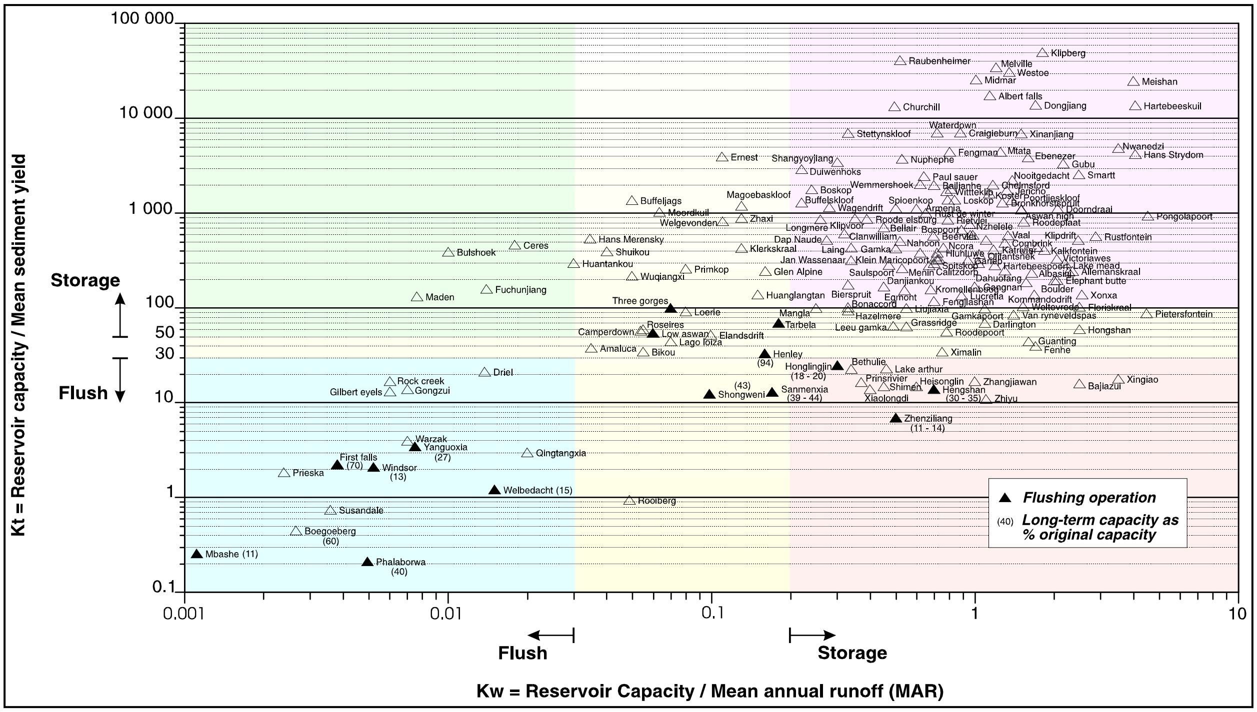


Figure 2.1-3 Dams with different modes of operation

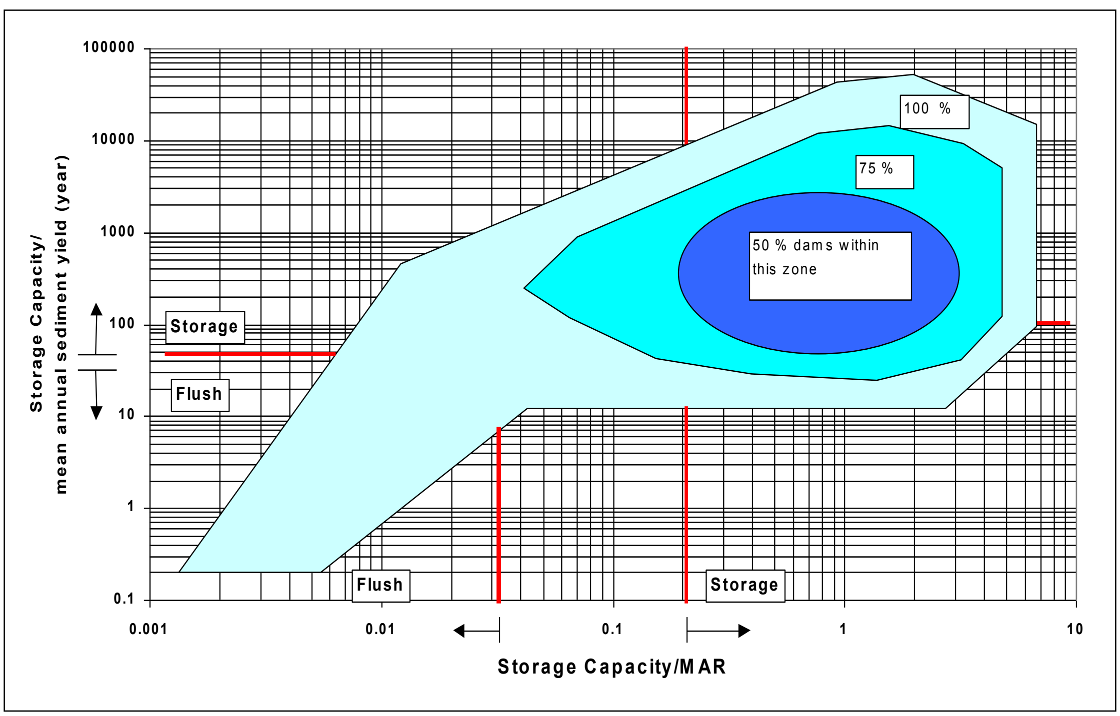


Figure 2.1-4 Empirical reservoir classification system in terms of storage, runoff and sediment yield

2.2 State of reservoir sedimentation

This report deals with the collection of international dam data and the attempt to quantify the current state of international dam sedimentation levels, as well as to make an effort to predict the loss of capacity at a future date, by using observed and recorded data and sediment yield patterns.

For most dam schemes around the world there are concerns that the rate of loss of storage capacity, due to sedimentation, is much larger than was catered for in the original design. This will in effect reduce the lifespan of these dams considerably. The majority of dams that are built allow for a dead storage to "ensure" that sediment build up will not interfere with the workings of the dam for a minimum period of time; this will vary from country to country. However, there is no guarantee that sediment will settle in this specified zone and, as a result of this, impacts on productivity (for hydropower schemes) have been seen to occur much sooner than anticipated.

Official international dam sedimentation data varies with typical values of dam sedimentation rates of 0.3% to 2% of the original dams' capacity being lost per year, which gives most dams roughly a lifetime of 100 years.

The objectives of this section are to:

- Collect international dam sedimentation data.
- Analyze this data in order to obtain an estimate of the current level of sedimentation of international dams.
- Calculate the rate at which dams are losing capacity annually.
- Couple this rate of storage loss with the sediment yield, in order to develop an empirical method that can predict future dam sedimentation on a regional basis so as to identify critical world regions.

This report and the conclusions drawn from it are limited due to the following factors:

- The scarcity of information relating to capacity surveys.
- The data that is available is generally from the 1980's and thus might not give a true reflection on the sedimentation rates as they might currently stand.
- For many countries, data was only available on a small proportion of the dams in that country, so the averages may not truly be representative to all the dams in the country as a whole.
- The dams' catchments size and geophysical features were not considered in this investigation.
- The trapping efficiency of dams was assumed to be 100% and the fact that dams silt up at a slower rate as they become older was neglected (which decreases the trapping efficiency over time).
- The effects of more than one dam along a river were not considered (reduced amount of sediment flowing to the lower dams etc…).

In the method that is developed dams that are in 2 countries (Kariba in Zimbabwe and Zambia, etc) are seen to show different sedimentation rates when calculations were made about sedimentation levels. This cannot be correct, but within the scope of this investigation it was deemed satisfactory, as this does not occur very often.

Reservoir sedimentation could lead to raised flood levels and in some cases towns had to be partially impropriated as flood levels rose significantly. A case study is the town of Weperner upstream of Welbedacht Dam on the Caledon River, South Africa. Bridges or abstraction warts sometimes also have to be raised due to raised flood levels by reservoir sedimentation. Other concerns are: decreased hydropower generation and turbine damage (abrasion), navigation problems, drainage of agricultural land.

2.2.1 Process of sediment accumulation behind dams

River systems erode material from the ground they flow over; these sediments are then transported downstream. When a river is dammed, the speed of the water is slowed down and thus the rivers ability to transport these sediments is reduced. When the speed is too slow the sediments in the river water will begin to settle out. The largest particles will settle out first, near the upstream end of the dam, and often cause what is known as a backwater delta. The finer suspended colloidal material (silts and clays) will settle out closer to the dam where the velocities are even lower. Some of the finer particles will remain in suspension and will flow through/over the outlet structures. The backwater delta will move forwards towards the dam wall as time progresses. Figure 2.2-1 shows a simplified version of how the sedimentation occurs.

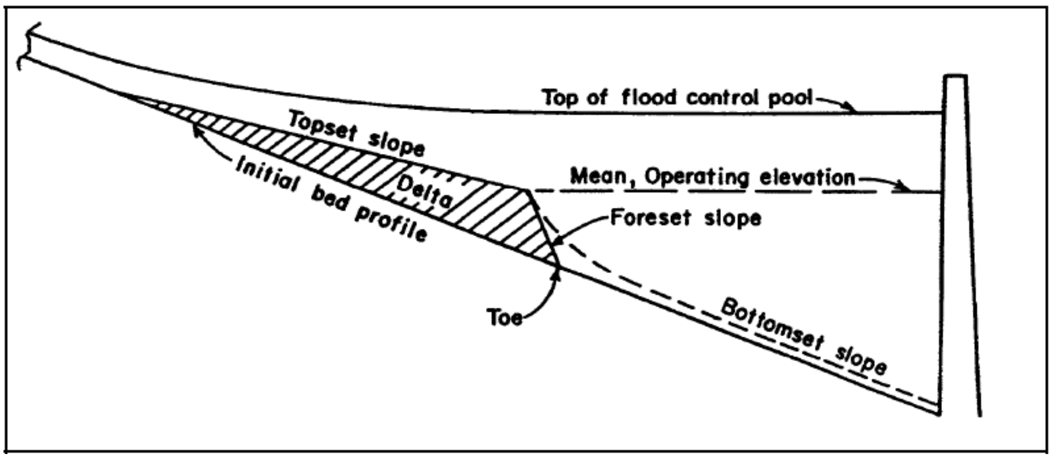


Figure 2.2-1 Conceptual deposition in deep reservoirs (USACE, 1997)

Every dam has a unique "trap efficiency". This refers to the proportion of the sediment flowing into the dam that is trapped behind it. Most large dam schemes have trap efficiencies close to 100%, although some dams where the ratio of Capacity to Mean Annual Runoff is very low could have trap efficiencies lower than 20%.

The rate at which reservoirs lose capacity due to sedimentation is generally expressed as a percentage of initial storage capacity lost per year. For example, if a dam is silting up at a rate of 0.6 %/ year, this means that when the reservoir is 50 years old approximately 30 % of the dam's initial storage capacity would be lost.

2.2.2 Methods of measuring dam sedimentation rates

The methods of measuring sedimentation rates have evolved as modern technology has improved. The current method, which is very accurate, is an adaptation of the bathymetric survey. This method now entails a differential global positioning system (DGPS) that is linked, through a laptop computer, to an echo sounder which is all mounted onto a boat. This system will take accurate X, Y and Z readings (to within a centimeter of the actual position) along a predetermined grid that covers the entire reservoir surface. These values are then plotted by the computer to form a very accurate current capacity curve (or contour map) of the reservoir. An example of what this capacity curve looks like is shown below in Figure 2.2-2. This particular example was taken from the bathymetric survey conducted of the Nyumba ya Munga reservoir in Tanzania (Belete K., et al, 2006).

This capacity curve is then compared with the "as built drawing" to calculate the total loss in storage capacity over time. It is assumed that this loss of capacity is solely because of sediment deposition. The older methods used for these surveys were very time consuming, not as accurate and depended largely on line of sight. With these new methods it is now easier to measure sedimentation rates, so one should expect to see improved data records emerging in the future.

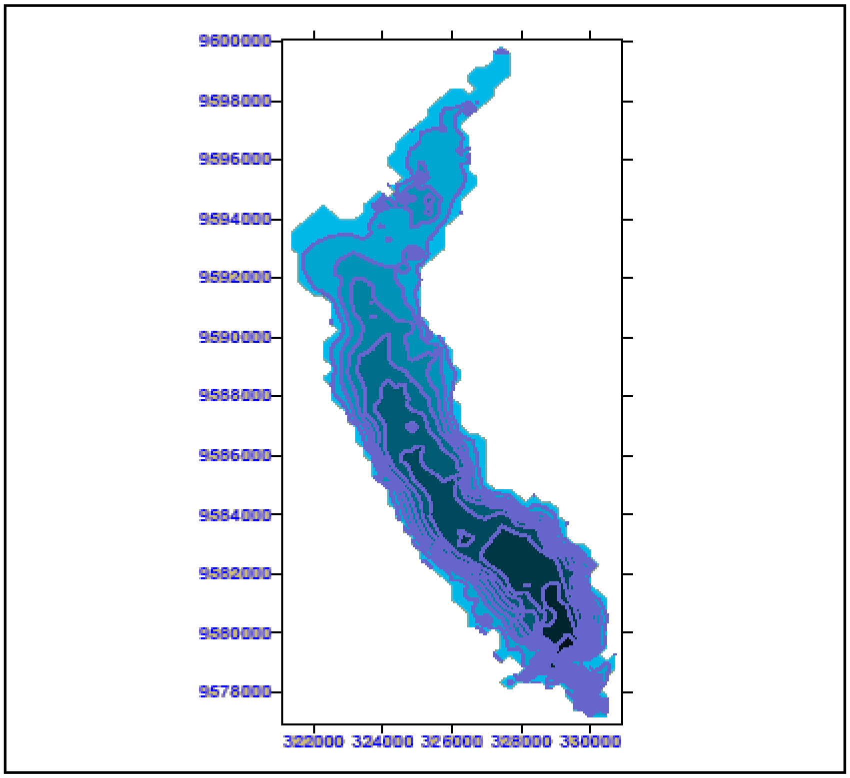


Figure 2.2-2 Contour Map of Nyumba ya Munga reservoir in Tanzania (Belete K., et al, 2006)

2.2.3 Sedimentation variability

The variability that is encountered when trying to quantify the sedimentation rate of a reservoir is the cause of many headaches for researchers and is the reason that no accurate method has yet been developed to predict the sedimentation rate. The most pertinent reason for this is the varying sediment yield from across countries and even provinces/states. Two dams that are close together in terms of distance can have vastly differing rates of sedimentation deposition. These differences are difficult to predict due to the lack of long enough databases, which is a result of the high expense and difficulty of conducting the necessary measurements. Hence, it is only in exceptional cases where an accurate data record is available. It was stipulated, by Professor K. Mahmood of George Washington University in Washington DC (McCully, 1996), that dam planners should ideally have sediment statistics going back over a period equal to at least half the projected life of the dam.

In the past a bathymetric survey was a major process and took weeks, if not months to conduct. This fact made it difficult to measure dam sedimentation rates, and this is why there is a shortage of global information on this topic. With the new methods mentioned in section 0 above, a large number of surveys should be conducted so as to better understand the situation. This information will enable governments around the world to better manage the reducing volume of water storage and also allow dam planners to more accurately predict at what rate a planned reservoir will lose capacity due to sediment accumulation.

A study done in India on 67 reservoirs for which the design sedimentation rate was known showed the following (Mathur P.C., et al, 2001):

Table 2.2-1 : Observed rates of sedimentation in India

Actual rate of sedimentation	less than	the design rate of sedimentation	8	reservoirs
Actual rate of sedimentation	1-2 times	the design rate of sedimentation	13	reservoirs
Actual rate of sedimentation	2-3 times	the design rate of sedimentation	14	reservoirs
Actual rate of sedimentation	3-4 times	the design rate of sedimentation	8	reservoirs
Actual rate of sedimentation	4-5 times	the design rate of sedimentation	8	reservoirs
Actual rate of sedimentation	more than 5 times	the design rate of sedimentation	16	reservoirs

This shows that the methods used in predicting the rates of sedimentation, for 59 of the 67 reservoirs tested, is highly optimistic and often can be completely wrong. The impact of this under-estimation is that the useful life of the reservoir will be shortened considerably. This is due to the fact that sediment will effectively fill the dead storage within a much shorter time frame than was previously estimated. The need for accurate prediction methods is clear when presented with the above data from India.

2.2.4 Global tendencies

The problem of reservoir sedimentation has been, and will continue to be, underestimated for the majority of reservoir schemes. The following statement is an extract from a recent copy of The International Journal on Hydro Power and Dams from an article concerning the sustainability of dams: "existing reservoirs lose 0.5 to 1.0 percent of their storage yearly and are on average already 35 years old; the best dam sites have already been used and the yearly increase of storage does not and will not balance the yearly loss by sedimentation" (Lempérière F., 2006). The article disputed this statement and showed (using a long string of calculations/assumptions) that an effective annual storage loss of approximately 0.3 percent was more realistic.

The data gathered during this investigation will hopefully be able to show, based on actual surveys that have been conducted, what the actual rate of storage loss per year is. The methods used to predict sediment accumulation rates will hopefully provide a more accurate method than just using an estimated "global average" expected rate.

2.2.5 Collection of data

As previously mentioned the availability of dam sedimentation data is very limited and most of the available data was gathered any time from the 1960's till the present. This means that whilst the data is most probably very accurate, it is possibly outdated and the trends and rates of sedimentation may be different now than they were when the surveys were done. The data collected for this bulletin was obtained from the following sources:

2.2.5.1 The internet

A large proportion of data obtained for this report was available on the internet. The main bulk of information attained was from the International Commission on Large Dams (ICOLD) website which had to do with data from all the member country's including information about Reservoir capacity, Year of completion and Installed Electric Capacity, to name a few. This data was downloaded from the World Register of Dams.

2.2.5.2 Published reports

Numerous countries are concerned about the impacts of storage losses due to sedimentation. These countries have conducted independent surveys to evaluate the state of their reservoirs sedimentation levels. These results have been placed in reports. Some of the information that was obtained from the internet was in the form of these reports; there were also a few "hard-copy" reports utilized as well. Two of the countries that had such reports were India and Puerto Rico.

Another useful report that was utilized extensively was a report by ICOLD's Committee on Reservoir Sedimentation which is made up of References and Sediment Yield data that was contributed by ICOLD member countries during the 1980's.

2.2.5.3 Electronic information

Reservoir basin survey data was received by the ICOLD Sedimentation Committee from Algeria, Pakistan, Japan, Italy and South Africa.

2.2.6 Analyzing data from sedimentation surveys

The data collected on sedimentation rates was gathered from many different countries. There is no standard method of quantifying dam sedimentation rates; hence, it was necessary to first format the data into a standard format so as to compare them correctly. For this investigation it was chosen to look at the storage capacity loss rate per year, a general formula for this is:

$$\text{Sedimentation rate (\% loss/yr)} = \frac{(C - C')*100}{(C * N)}; \qquad (1)$$

Where:
C = Original capacity (at time of construction);
C' = Current capacity (at time of most recent sedimentation level survey);
N = Age of the dam (Year of last survey – Year of construction);

The bulk of the data that is used is often from a number of years ago, so the sedimentation rates obtained for the respective countries will more than likely not give a current updated view of what the levels and rates actually are.

A detailed look at what was actually done to the data from each source is provided below.

2.2.6.1 South Africa

The database of South African dams, is one of the most complete databases that was used in this investigation. The database was screened on the basis of the trapping efficiency. There are numerous dams in South Africa that have a low capacity to Mean Annual Runoff (MAR) ratio. These dams were not considered for the purposes of calculating average sedimentation rates because the trapping efficiency for them was seen to be less than 20%, and the volume of sediment that is trapped by these reservoirs, is considered negligible.

The data for South Africa shows the sedimentation rates for 121 dams. The ICOLD World Register of Dams shows that 915 dams are registered as “large” dams in South Africa. This means that the dams used to predict the average sedimentation rate represent roughly 13 % of the dam population.

The equation (1) above was applied to each dam and then the average of the results was taken. The average value of the sedimentation rate in South Africa was seen to be = 0.37 %/yr.

2.2.6.2 Algeria

Data was available for 49 dams from Algeria. Of these 49 dams it was only possible to calculate the sedimentation rate using data for 40 of the dams. This is because the remainder of the dams showed sedimentation rates of 0 %/yr. These dams also happen to be the youngest. The probable explanation for the outcome of 0 %/yr is that the dams were not included in the most recent surveys, which were conducted in 2000.

According to the ICOLD World Register of Dams there are 114 large dams in Algeria. Thus, 35 % of dams are represented by the average sediment yield rate. This rate was calculated using the average value of the results of equation (1) after it was applied to each individual reservoir, it was found to be 0.81 %/yr;

2.2.6.3 Food and Agriculture Organization (FAO)

The FAO is very interested in the accumulation of sediment in reservoirs due to the direct implications on the decrease of water available for Irrigation of crops. Two databases were available for the purposes of this investigation. The usefulness, as well as the results obtained from these two databases, is discussed below.

2.2.6.3.1 Database of World Rivers and their sediment yields (FAO, 2006).

This is an international database and so was very useful for the purposes of this investigation. Besides for Morocco the data is for a small number of dams which means that (especially for the larger countries) the data might not give an accurate representation of the rates in the respective countries.

Table 2.2-2 : Data from FAO (2006)

Country	Number of Reservoirs	Average Sedimentation rate (%/yr)
China	7	6.64
Ethiopia	1	0.52
Kenya	4	1.45
Morocco	17	1.08
Nepal	1	1.00
Philippines	2	0.84
Sudan	2	2.66
Tanzania	1	3.27
Thailand	3	1.42

2 above lists the results that were obtained when equation (1) was applied to the data that was available for each country. When possible this data was added to, with information from other sources, but that was only possible for China, Morocco and Sudan.

2.2.6.3.2 AQUASTAT – List of African Dams (FAO, 2006).

This database is a very comprehensive list of the dams in Africa. Similar to the ICOLD World Register of Dams, it lists the Nearest Town and State/Province. However, unlike the ICOLD register the co-ordinates of the dams are provided. This provides accurate information about the location of the dams in the database. One of the other fields of importance in this database is the Level of Sedimentation field. This gives the level of sedimentation as a percentage. Unfortunately, the date at which the level of sedimentation was determined is not supplied. This means that, for the few dams on which sedimentation data was available, it is impossible to calculate a sedimentation rate. So for the purposes of this study this database is not very useful. The countries which had information relating to sediment levels from this database are Algeria, Morocco, South Africa, Sudan and Tunisia.

2.2.6.3.3 Academy of Agriculture of France

A report about the consequences of sedimentation was written for the French Academy of Agriculture (Margat J, 2002). This report contains a table which gives information about the initial capacity, capacity lost due to sedimentation as well as the annual rate of capacity loss for various countries. A shortened version of this table is shown below as Table 2.2-3. It lists the countries that are included, the reservoirs in the country's that were surveyed and the rate of loss of capacity in those countries.

Table 2.2-3 : French Academy of Agriculture (2002)

Country	Reservoir	Annual Loss of capacity	
		hm^3/an	%
Algeria	19 Dams (1882-1978) 1957 1995 (24 Dams) 2000	14.8 30 	0.8 0.5 - 1 0.7 2 to 3
China	Sum of Dams 236 Dams in 1981	2.3 0.8	
Egypt	Aswan (1964-1990)	80	0.046
Spain	101 Dams (1980-1994)		<0.1 - 4
France (1990)	Rhone Bassin Serre-Poncon Le Sautet L'Escale	 0.83 0.37 0.42	 0.07 0.28 2.8
India	8 Dams		0.6 (0.3 - 1.4)
Morocco	78 Dams (1992) 29 Dams (1998) 25 Large Dams in 2000	50 38 65	0.5 0.4 0.45
Pakistan	Tarbela (1974)	130	0.9
Tunisia	El Kebir (1930) Dams (1998)	0.4 28	1.35 1.75 (1 - 2.5)
USA	Dams with a CAP. >6.2 hm^3 USA (roughly 1985) "Mountain States" (Arizona, Colorado, N.Mexico, Nevada…) "Pacific States" (California, Oregon…)	2020 373 544.5	0.22 0.18 0.49

It was decided that this data would only be used for countries that lacked other, more detailed data sets. It turned out that the average sedimentation rate for Egypt, France and Tunisia were used.

2.2.6.4 ICOLD 1980

This document was compiled by the ICOLD Committee on Reservoir Sedimentation and is made up of References and Sediment Yield data that were contributed by ICOLD member countries during the 1980's (ICOLD, 1980). This document has data for many countries around the world and includes River Loads, and Reservoir deposits. The reservoir deposit information was crucial for the purposes of this bulletin, as it provided additional data from numerous countries which improved the overall global representation of this study. The country's, for which information was utilized, as well as the average sedimentation rate and the number of dams used to calculate these average rates, are shown in Table 2.2-5 below:

Table 2.2-5 : ICOLD 1980 data

Country	No. of dams	Loss %/yr
Australia	5	0.64
Germany	8	0.17
Korea	13	0.26
New Zealand	5	1.14
Poland	6	0.62
Spain	21	0.46
Thailand	5	0.55
Botswana	3	1.08
Zimbabwe	10	0.22

For Botswana and Zimbabwe information was provided regarding the name of the reservoir, the catchment's area (km^2) and the 50-year sediment yield (tonnes/km^2/yr). The 50-year sediment yield was converted to volume deposited per year (m^3/year) by multiplying the Sediment yield by the catchment's area and converting it to a volume (assuming that the relative density of the sediment was 1.35 tonnes/m^3). This was assumed to be the volume of sediment deposited each year in the respective dams.

It was then necessary to search on the World Register of dams to find information about the year of completion, and also the reservoir capacity (1000 m^3) for the dams in question. The volume of sediment accumulated in the dam, over its life thus far, was calculated by multiplying the volume of sediment deposited each year by the age (from year of completion up till 2006).

The final step to obtain the sedimentation rate was to express the volume of sediment accumulated as a percentage of the reservoir capacity and to divide it by the age of the reservoir. This yielded the average rate of loss of storage capacity in percentage per year (%/year).

2.2.6.5 Compendium on Silting of Reservoirs of India

This is a book published by the Central Water Commission of India (Mathur P.C., et al, 2001). It focuses primarily on the effective management and planning of water resources. It is a comprehensive effort to establish the current state of the reservoirs in India (in terms of storage capacity loss). The Annexure of the compendium contain the data that was compiled through capacity surveys conducted on 144 dams throughout India. The average rate was worked out for India as a whole and on a provincial scale as 0.72 %/yr.

On a region wide basis the loss rates were, as given below in Table 2.2-6:

Table 2.2-6 : Provincial data for India

Province/State	No. of dams	Loss (%/yr)
ANDHRA PRADESH	13	0.81
BIHAR	4	0.37
GUJARAT	46	0.82
HIMACHAL PRADESH	1	0.31
KARNATAKA	5	0.32
KERALA	15	0.64
MADHYA PRADESH	1	0.27
MAHARASHTRA	21	0.49
MEGHALAYA	1	0.32
ORISSA	2	0.47
PUNJAB	1	0.35
TAMIL NADU	28	0.77
UTTAR PRADESH	5	1.55
WEST BENGAL	1	0.52
Total	144	
Average		0.72

2.2.6.6 Sedimentation of Reservoirs in Japan

The Japanese database shows that Japan is taking the loss of storage capacity in its reservoirs very seriously and that they wish to have an accurate account of where the country stands at present. This is because bathymetric surveys were conducted on all the dams in the database in 2002 and again in 2003. The ICOLD World Register of dams shows that Japan has 1171 “large” dams. The database that was provided by Japan has detailed information on 420 dams, which is a 35% representation of the “large” dams. The data provided gives the year of completion, the capacity of the dam (original capacity, 2002 capacity and 2003 capacity) in 1 000 m^3. Using this data it is possible to calculate the average rate of loss of capacity in Japan by applying equation (1) to every dam and then calculating the average of these loss rates. It was seen that for Japan the sedimentation rate is 0.42 %/yr.

2.2.6.7 Puerto Rico

An investigation by United States Geological Survey (USGS) and the Puerto Rican Government on 14 of the principal reservoirs in Puerto Rico (Soler-López L.R., 2001) was undertaken since 1994. This was an attempt to quantify the rate of loss of storage capacity and the potential impacts on power generation, irrigation as well as domestic and industrial water supplies. Hurricanes and other tropical disturbances cause major floods that rapidly increase the sedimentation rate.

The results of this study, which comprised of bathymetric surveys on all 14 of these reservoirs, provided a useful source of information about sedimentation rates on tropical islands (specifically in the Caribbean). The sedimentation rate was found to be 0.74 %/yr.

2.2.6.8 Iran

The data that was found for The Islamic Republic of Iran was a presentation that was prepared by the Water Research Institute. The presentation included a map showing the location of the major dams in Iran (Water Research Institute, 2005), this is shown below as Figure 2.2-3:

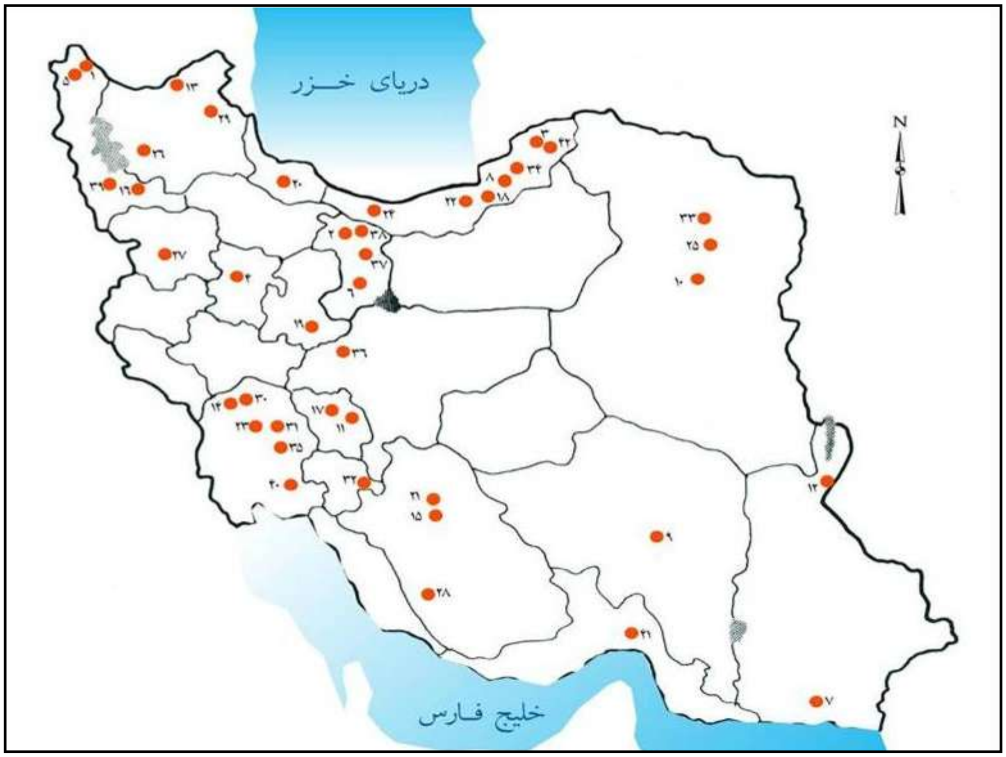


Figure 2.2-3 Location of dams in Iran (Water Research Institute, 2005)

The data from this presentation was consolidated into a single table. From this data it was shown that the average sedimentation rate in Iran, based on the data from the 23 dams provided, is 1.65 %/yr.

2.2.6.9 United States of America

The data that was obtained is listed below in Table 2.2-7. This table shows the data obtained by state, with the source of this information referenced, the number of dams used to obtain the averages and the average sedimentation rate.

Table 2.2-7 : State sedimentation rates, America

State	No. of dams	Loss (%/yr)
Indiana (Wilson J.T., et al, 1996)	2	0.45
Illinois (Bogner W.C., 2001)	1	0.4
California (Snyder N.P., et al, 2004) (Devine Tsrbell, et al, 2005)	2	0.61
Maryland (Ortt R.A., et al, 1999)	2	0.125
Kansas (Mau, D.P., et al, 2000)	4	0.28
Texas	72	0.36
Hawaii (Wong M.F., 2001)	1	0.84

Morris (1998) stated that the national average sedimentation rate of American reservoirs is 0.27 percent per year. It was decided to examine America by state, rather than use a single average over the whole country. However, a weighted average of the sedimentation rates obtained above was found to be 0.36 %/yr.

This average is largely influenced by the number of data points available from Texas. So it cannot really be considered to be a good representation for the whole of America.

The database from the Texas Water Development Board was the most comprehensive data found for America, it compiles the bathymetric survey data from surveys that have been systematically conducted since 1993.

2.2.6.10 Summary

The data that was obtained, from all the various sources and methods described above, was compiled in order to show the current sedimentation rate for countries where data was available. The results are best summarized in a graphical form, as shown below in Figure 2.2-5 which also shows the number of dams that the averages were obtained from, as well as the source name. The rates are well below 1.0 % loss/ year for most of the countries, however there are countries such as Tanzania and China that have sedimentation rates well above 2.0 % loss/ year.

Tanzania's rate is very high because it is the sedimentation rate for just one reservoir. The rate for other reservoirs in Tanzania could possibly be much lower, so the situation might not be as bad as it appears.

The average sedimentation rate for China is based on information from 29 dams. Two of those dams show exceedingly high sedimentation rates; these rates are 18.37 %/year and 12.12 %/year. These outliers push the average rate for China up to the given value of 2.9 %/year. The rate in China is, however, expected to be high so this rate might not be too far off the actual sedimentation rate for Chinese dams and there are relatively high rates of sediment yield over most of China.

Taking an average from these values for each respective country to obtain a global average (based on the best available data) yielded a sedimentation rate of 0.96 %/yr.

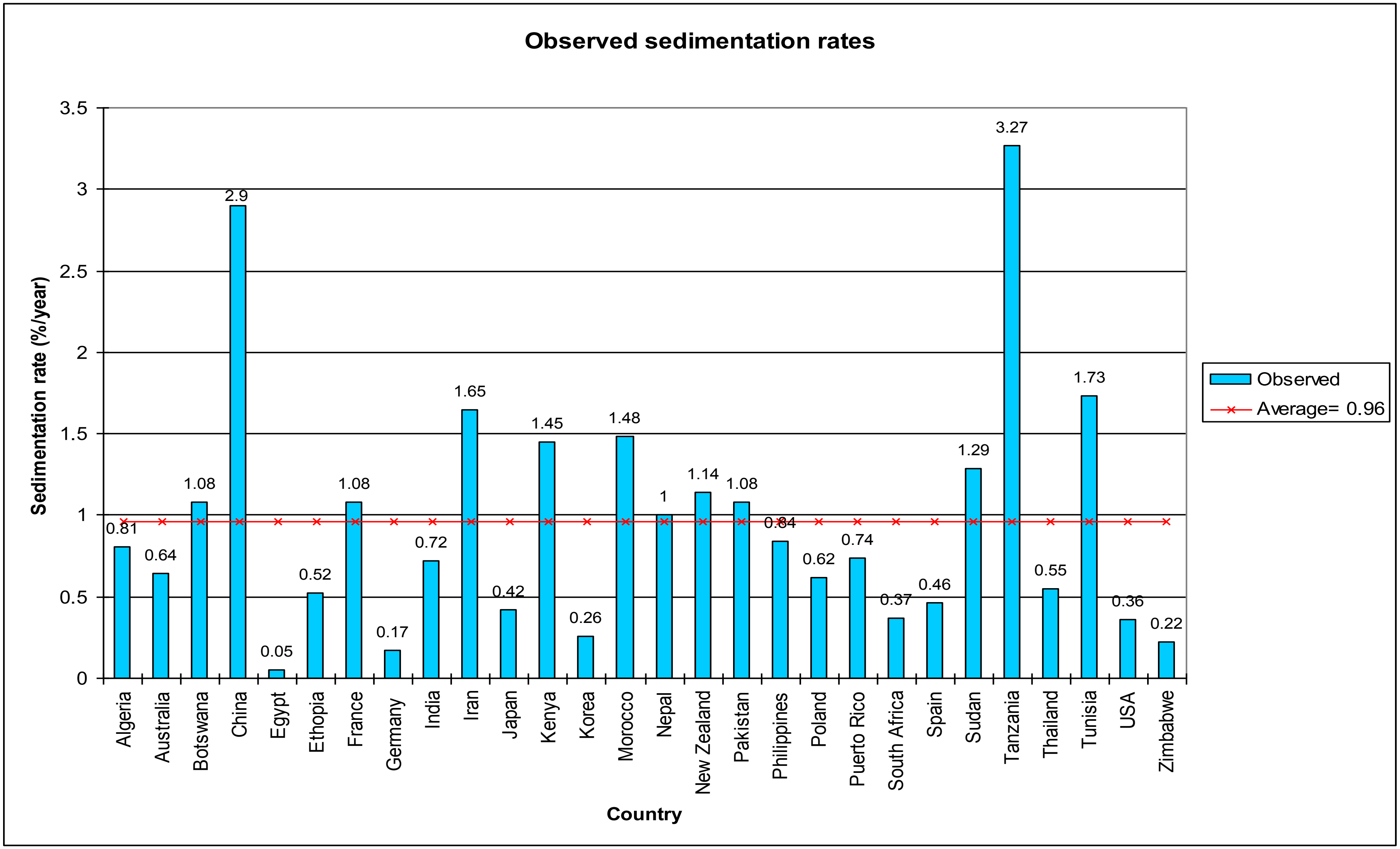


Figure 2.2-4 Observed sedimentation rates

The countries from which this rate was calculated have a relatively even distribution around the globe, with all the continents being represented except for South America. The average sedimentation rate of 0.3 %/year that was postulated earlier in paragraph 0 from the excerpt out of The International Journal on Hydro Power and Dams seems to be a good deal lower than the rate obtained from actual measurements and surveys.

2.2.7 Scaling and applying sedimentation rates

The next step in this investigation involved coupling the sedimentation rates, obtained above, with sediment yield information in an effort to predict the sedimentation rate that will occur at a specific place, given information about the sediment yield and other dam characteristics. The first step was to find a map that showed the global patterns of sediment yield. The selected map was taken from the work of Walling and Webb, 1983, and is shown below. (This map was found in a report by Hartmann, 2004.)

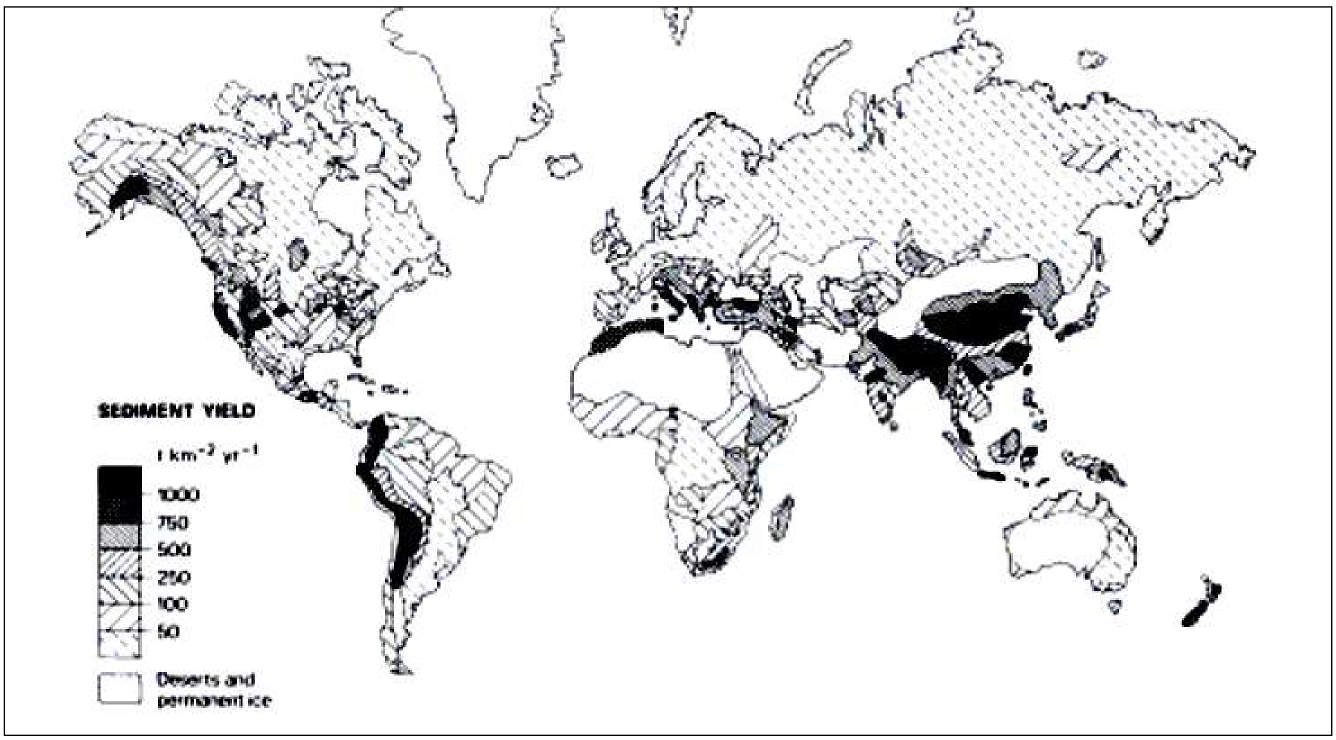


Figure 2.2-5 Global Patterns of Sediment Yield (Walling and Webb, 1983)

The map shows eight different sediment yield zones with the units of tonnes per square kilometer per year (t/ km^2.year). The map is shown above as Figure 2.2-5. The range of sediment yield starts at Deserts and Permanent Ice through to 1000 t/ km^2.year and upwards. The upper limit was not specified so it was assumed that the upper value was 3000 t/ km^2.year.

2.2.7.1 Average sedimentation rates for sediment yield zones

In order to scale the sedimentation rates, it was necessary to first determine in which sediment yield zone the countries, for which data was available, were placed. This was done by superimposing a map of the world, showing country boundaries, onto the sediment yield map. The map that was used is shown below as Figure 2.2-6. Thus it was possible to determine the sediment yield rate for the various countries. The maps were not very large so it was difficult to accurately demarcate the country boundaries as well as the sediment yield zones within countries.

Figure 2.2-6 World map showing country borders (http://wgrass.media.osaka-cu.ac)

To try and accurately represent the sediment zones of large countries was difficult because each country can contain many different zones. Thus, it was decided to split some of the larger countries up by state/province. The countries for which this was done are:

- India
- South Africa
- United States of America

The countries were then grouped together according to their sediment yield zone. It often occurred that more than one sediment yield zone was present in a single country or state, as mentioned earlier. If the majority of area of a country lay in, for example, the sediment yield zone of 100 - 250 t/ km^2.year, then the country was classed as having a sediment yield zone of 100 - 250 t/ km^2.year. However, when it occurred that 2 or even 3 different zones were present in similar proportions over the area of a country, a single zone could not be chosen. As a result of this is was decided to use a system of weighted averages to calculate the average sedimentation rates for the different zones.

An example (not the full data for sediment yield zone 100 - 250 t/ km^2.year, just for illustrative purposes) is provided below to describe the method more fully:

The following countries/states are present in the sediment yield zone 100 - 250 t/ km^2.year: Botswana, Zimbabwe, Texas (USA) and Sudan, to name a few.
Botswana and Zimbabwe lie mainly in the 100 - 250 t/ km^2.year zone, however there are small areas that lie outside this zone, but since the large majority of the area is in the 100 - 250 t/ km^2.year zone, this is taken to be its sediment yield. Texas (USA) and Sudan are seen to have roughly half of each of their respective areas lying within the 100 - 250 t/ km^2.year zone.

The sedimentation rates for the countries/state were calculated earlier and are listed below:

- Botswana : 1.08 %/ year;
- Zimbabwe : 0.22 %/ year;
- Texas (USA) : 0.36 %/ year;
- Sudan : 1.29 %/ year;

Now, to compensate for the whole of Sudan and Texas not being of the zone in question, the weighted average was calculated as follows:

$$\text{Weighted Average} = \frac{\text{Sum of sedimentation rates}}{\text{Sum of proportions of areas}};$$

$$= \frac{(1.08 + 0.22 + 0.36 + 1.29)}{(1 + 1 + 1/2 + 1/2)};$$

$$= \frac{2.95}{3};$$

$$\approx 0.98\ \%/\ \text{year};$$

This rate was then assumed to be valid for all countries that lay in the sediment yield zone 100 - 250 t/ km^2.year.

The above method was applied to all the sediment yield zones and all the data calculated previously and the results that were obtained are summarized below in Table 2.2-8, with the full calculations laid out as in the Appendix. The only countries that could not be utilized were the Philippines, Japan and Puerto Rico, because of the size of the map; it was unclear in what zone these island countries lay.

Table 2.2-8 : Sedimentation Rates from Sediment Yield Zones

Sediment Yield Zone (t/km^2.year)	Average sedimentation rate (%/ year)
Desert and permanent ice	1.33
0 – 50	0.6
50 - 100	0.63
100 - 250	0.68
250 - 500	0.64
500 - 750	0.8
750 - 1000	1.72
1000 - 3000	0.89

2.2.7.2 Applying the sedimentation rates to dam data from various countries

The average sedimentation rates that were obtained above were now used to calculate the current situation of dams (2006) and the situation as it could be in the year 2050, in most of the countries around the world. In order to do this it was necessary to obtain detailed data for the reservoirs from as many countries as possible. The ICOLD World Register of Dams was used. Data from roughly 33 000 dams is available for download from the register.

An example of the relevant fields, ones that were used during calculations, is provided below:

Table 2.2-9 : World Register of Dams; Relevant fields

Dam name	Country name	Year of completion	Reservoir capacity (1000 m3)	Reservoir catchment (km2)	Reservoir purpose	
ABAYA	Tunisia	1993	1670	16	I/R	
EL AROUSSIA	Tunisia	1957	5000			H

The data was downloaded by Continent in alphabetical order. So, for example, in the Africa spreadsheet there are worksheets for all the African countries (that appear on the register) from Algeria through to Zimbabwe. The same holds true for the other continents and regions and they are listed below:

- Africa
- Asia
- Australia and Oceania
- Central America
- Europe
- The Middle East
- North America
- South America

A list of the countries represented by the World register, and consequently this database, is provided below as Table 2.2-10. The countries have been separated depending upon which region they fall into as is commonly practiced in geographic terms.

The larger countries were once again split by state/province. This was done for Brazil, Argentina, China and Canada.

Table 2.2-10: Countries included in database

Region	Countries			
Africa	Algeria	Ethiopia	Mali	Sudan
	Angola	Gabon	Mauritius	Swaziland
	Benin	Ghana	Morocco	South Africa
	Botswana	Guinea	Mozambique	Tanzania
	Burkina Faso	Kenya	Namibia	Togo
	Cameroon	Lesotho	Nigeria	Tunisia
	Congo	Liberia	Senegal	Uganda
	Cote d' Ivoire	Libya	Seychelles	Zambia
	Democratic Republic of Congo	Madagascar	Sierra Leone	Zimbabwe
	Egypt	Malawi	Somalia	
Asia	Bangladesh	Laos		
	Brunei	Malaysia		
	Cambodia	Myanmar		
	China	Nepal		
	India	Phillipines		
	Indonesia	Singapore		
	Japan	Sri Lanka		
	Kazakhstan	Thailand		
	Korea – North	Vietnam		
	Korea – South			
Australia and Oceania	Australia			
	Fiji			
	New Zealand			
	Papua New Guinea			
Central America	Antigua	Nicaragua		
	Costa Rica	Panama		
	Cuba	Puerto Rico		
		Trinidad and Tobago		
	Dominican Republic			
	El Salvador			
	Guatemala			
	Haiti			
	Honduras			
	Jamaica			
	Mexico			
Europe	Albania	Denmark	Latvia	Russia
	Armenia	Finland	Lithuania	Serbia
	Austria	France	Luxemborg	Slovakia
	Azerbaijan	Georgia	Macedonia	Slovenia
	Belgium	Germany	Moldavia	Spain
	Bosnia and Herzegovina	Greece	Netherlands	Sweden
	Bulgaria	Hungary	Norway	Switzerland
	Croatia	Iceland	Poland	Ukraine
	Cyprus	Ireland	Portugal	United Kingdom
	Czech Republic	Italy	Romania	
Middle East	Afghanistan	Tajikistan		

	Iran Iraq Jordan Kyrgzstan Lebanon Oman Pakistan Saudi Arabia Syria	Turkey Uzbekistan		
North America	Canada			
	United States of America			
South America	Argentina Bolivia Brazil Chile Colombia Ecuador Guyana Paraguay Peru Suriname	Uruguay Venezuela		

The calculations that were performed on the reservoirs from each country are the same throughout so, to avoid unnecessary repetition, the procedures followed to perform these calculations will be explained for Ukraine, as a random example.

2.2.7.2.1 Calculation steps

Once the raw data was downloaded from the register, the first step was separating the Reservoir Purpose column into two columns. One was for Hydropower dams, and the other was for all other purposes. Dams often have multiple purposes, with most Hydropower schemes being used for water storage and irrigation as well. However, to get an idea of how the growth of storage capacity for reservoirs has evolved over time it was interesting to see the differences between dams built for various purposes. If a dam was seen to have power generating capacity it was assumed that the primary purpose of this reservoir was power generation. Thus, a dam was classed as either a Hydropower dam or a dam for all other purposes.

Some of the other purposes are:

- I – Irrigation
- S – Storage
- F – Flood control

2.2.7.2.1.1 Sedimentation rates

After the purposes were separated, the following step was to assign the correct sedimentation rate for the country. This was achieved by locating Ukraine on Figure 2.2-6 and then superimposing this map upon Figure 2.2-6 and identifying which sediment yield zones were represented in the country, and in what proportions they appeared.

For Ukraine it was seen that $^2/_3$ of the country was represented by the 50 – 0 t/ km^2.year zone and the other $^1/_3$ of the country the 100 – 50 t/ km^2.year zone. This was done for all the countries, in all the regions listed above.

Now that the proportions of the zones have been identified for Ukraine, the next step is to calculate the sedimentation rate. This is done by factoring the Rates determined in Table 2.2- to achieve the rate for the desired country.
So for Ukraine:

Sedimentation rate = $^2/_3$(Rate for zone 50–0) + $^1/_3$(Rate for zone 100–50);
= $^2/_3$(0.6) + $^1/_3$(0.63);
= 0.61 %/ year;

Now that the sedimentation rate for the country had been determined, the predictions about the levels of sedimentation in the country could begin.

2.2.7.2.1.2 Prediction calculations for current and future sediment levels

The steps used will be placed below in the order they were conducted to arrive at the level of sedimentation in 2006 and the future level of sedimentation in 2050. The procedure was then conducted for all the dams in the country. The steps used are for the Balanovo dam in Ukraine and are provided below:

1. The Current Age (2006) of the dam was calculated by simply subtracting the Year of Completion from 2006.(For cases when no Year of completion was known, the year 1965 was used, as there was a boom in dam building worldwide in the 1960's).

   Age (2006) = 2006 – 1974;
   = 32 years;

2. Multiplying the Sedimentation rate (% storage loss per year) by the Current Age (2006) to calculate the Percentage loss of capacity up until 2006.

   % Loss of capacity (2006) = 32 years x 0.61 %/ year;
   = 19.52 %;

3. The Remaining capacity (1000 m^3) was calculated by multiplying the Percentage loss of capacity (2006) by the Reservoir Capacity (1000 m^3) , then subtracting this value from Reservoir Capacity (1000 m^3).

   Remaining Capacity (2006) = 5000 – (5000 x 0.1952);
   = 4024 (1000 m^3);

4. The Expected Remaining Life of reservoir was calculated by dividing 100 % by the Sedimentation rate, to calculate the total expected life, and then subtracting the Current Age from this value.

   Expected Remaining life = (100 ÷ 0.61) – 32;
   ≈ 132 years;

5. To calculate the Age at 2050, the Percentage loss of capacity up until 2050 and the Remaining Capacity at 2050 the steps 1 through 3 are used again, with the year 2050 being substituted for the year 2006.

   Age (2050) = 76 years;
   % Loss of capacity (2050) = 46.36 %;
   Remaining Capacity (2050) = 2682 (1000 m^3);

Once the above calculations were completed for each dam, the Total capacity of reservoirs in the country was summed. A summary of these results for Ukraine are shown below as Table 2.2-11.

Table 2.2-11 : Summary of Ukraine's Storage loss over time

	Reservoir capacity (1000 m^3)	Remaining Capacity (2006)	Remaining Capacity (2050)
TOTAL	46,884,550.00	33,106,529.72	20,522,716.50
Remaining	100.00%	70.61%	43.77%

In the above table, the Reservoir Capacity column shows the potential capacity of all the dams in the country if no sedimentation occurred. The second column shows the current capacity of dams with the sediment that has accumulated till the present, as well as expresses this remaining capacity as a percentage of the total capacity (without any sediment). The third column is the projected remaining capacity in 2050. This value is also expressed as a percentage of the total capacity.

As can be seen, if no actions are taken to mitigate the sedimentation rate (assuming that the rate applied in this method is accurate) , after the next 44 years there will be only 44 % of the capacity of the dams in Ukraine left unfilled by sediment.

2.2.7.2.1.3 Growth of reservoir storage capacity over time

An additional step that was taken was to formulate a table which shows the growth of dam storage capacity over time. The time intervals that were chosen were decades (10 – year blocks) and the starting date was selected as 1900. Although there are dams constructed prior to 1900 the volume of these dams in comparison with the volume of post-1900 dams, is almost negligible.

When representing the loss of storage volume over time, it was not possible to calculate accurately the volume lost per year, for each dam. Thus, a simplified method was used that assumed that all dams constructed during a decade were built at the start of that decade. Then the sedimentation rate of the country (Ukraine = 0.61 %/ year) was multiplied by 10 years to obtain a loss of storage of 0.061 times the capacity during that 10 year block. For example:

In Ukraine during the decade from 1930 to 1940 the storage capacity was increased from 0 m^3 to the value of 3320 x 10^6 m^3. Thus

Loss of storage (Volume of sediment) = (0.61 %/ year x 10 years) x 3320 x 10^6 m^3;
= 0.061 x 3320 x 10^6 m^3;
= 202.52 x 10^6 m^3;

The value of sediment accumulation during a 10 year block is then summed cumulatively as time progresses. If it occurs that no dams were constructed during a decade, then the sediment loss rate will remain the same as for the previous decade (because the storage capacity is the same) and be added to the cumulative loss of storage. Continuing with the Ukrainian example, Table 2.2-12 has been included to further illustrate the method used.

After the decade 2010 there is no more growth of dams as it is impossible to predict how large and at what rate dams will be constructed in the future. The projection of storage loss for reservoirs from 2010 until 2050 is the value of storage loss that will occur, even if no more dams are built.
Table 2.2-12 is better illustrated in a graphical manner as shown below in Figure 2.2-7.

Table 2.2-12 : Growth of storage capacity in Ukraine

	Storage Capacity (1000m3)	
Year (<)	Growth	Loss
1900	0	
1910	0	0
1920	0	0
1930	0	0
1940	3320000	202520
1950	3320000	405040
1960	21536000	1718736
1970	44282000	4419938
1980	46792500	7274280.5
1990	46884550	10134238.05
2000	46884550	12994195.6
2010	46884550	15854153.15
2020		18714110.7
2030		21574068.25
2040		24434025.8
2050		27293983.35

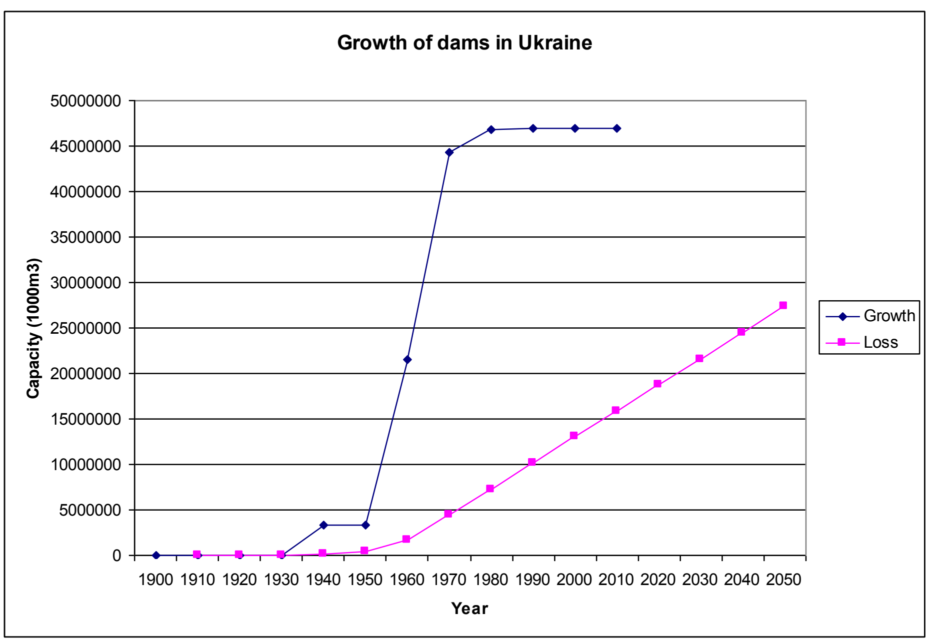


Figure 2.2-7 Growth of dams in Ukraine since 1900

It was noticed that up until 2010 the loss of storage was 15 854.15 x 10^6 m^3 and that over the next 40 years, the additional loss of storage, over and above this value, will be 11 439.83 x 10^6 m^3. This means that if Ukraine wishes to maintain the current storage capacity an increase in storage capacity exceeding 12 000 x 10^6 m^3 will need to be constructed. Regions that have a higher sedimentation rate than Ukraine are seen to have lost almost the total storage capacity by 2050.

This category of graph shows the rate at which countries constructed dams. It is seen that for Ukraine the rate of dam construction remained low until the 1950's, then during the 1960's and 1970's the bulk of the storage capacity for Ukraine was captured behind dams. There was a small increase in the capacity but, as can be seen from the graph, the rate levels off and no dam construction has taken place during the last 20 years. Thus, it can be said that after a period of acceleration of growth rate of dams, Ukraine's dam building has currently slowed down to a stop.

Comparatively, the sedimentation rate shows an ever increasing trend, and this clearly points out the questionable sustainability of dams over the long term.

The above procedure of showing the growth of storage capacity over time, as well as the loss of storage that goes hand in hand with it, was also conducted to show the growth of Hydropower dams over time and also the growth of dams for all other purposes. These values were plotted on the same graph so that the impact of sedimentation can be seen on the reservoirs built for different purposes. Figure 2.2-8 below gives an indication of the outcome of this comparison.

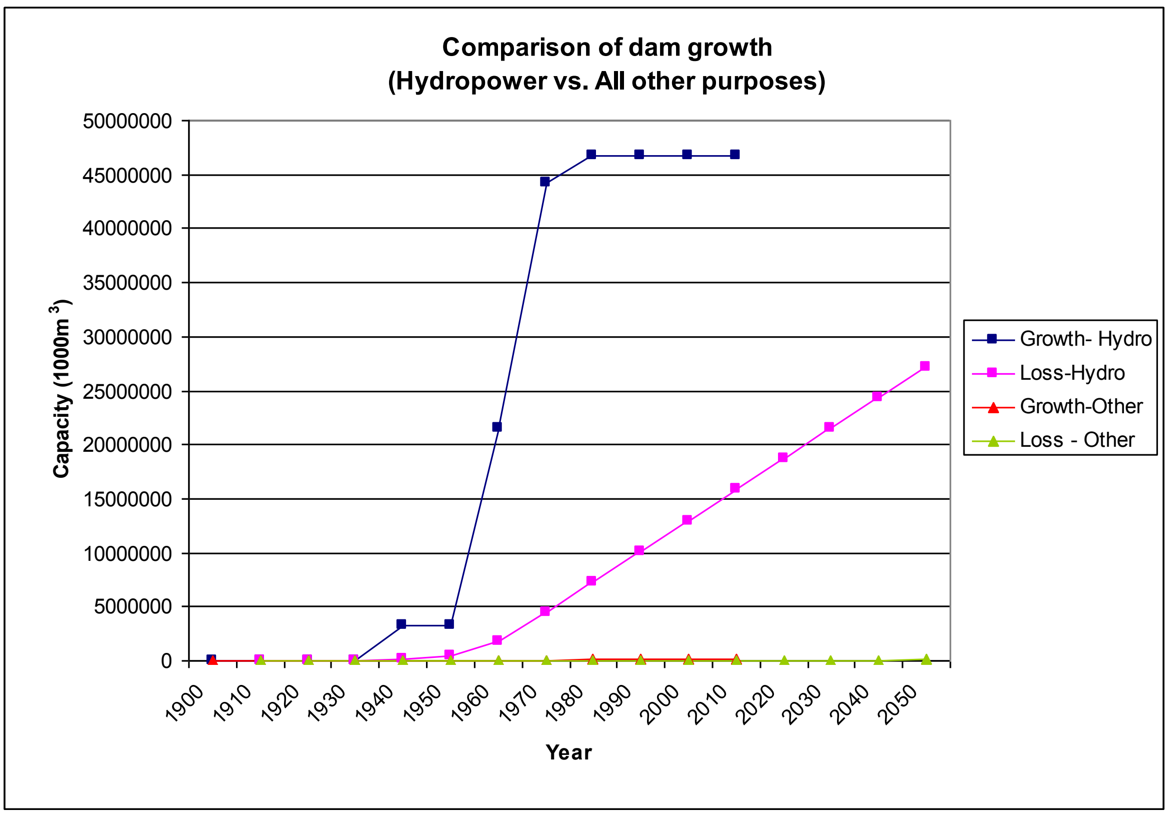


Figure 2.2-8 Comparison of the growth of dams used for different purposes in Ukraine

As can be seen above, in Figure 2.2-8, the bulk of the storage capacity in Ukraine is used for power generation. The storage capacity for all other purposes is practically negligible. By the year 2006, approximately 34 % of Ukraine's total hydropower storage capacity had been filled with sediment. This figure is projected to increase to a value of 58 % of the total hydropower storage capacity. The volume of storage lost on hydropower dams was, in 2006, 15 811 million cubic meters (mcm) and, in 2050, 27 209 mcm.

For all other purposes the loss of storage capacity by 2006 is 25 % of the total storage capacity which is a value of 42.8 mcm. This loss could increase to 49 % or a value of 84.5 mcm by the year 2050.

The calculation steps and the tables showing growth and loss rates for the country as a whole as well as the ones showing the comparison of dams by purpose were done for all of the countries that appear in Table 2.2-10. However, the graphs that are shown above were only compiled for the countries for which there were observed sedimentation rates, the countries that appear in Figure 2.2-4. (The graphs shown for Ukraine were compiled for the purposes of explaining the procedure and the results obtained from this procedure). The graphs for countries that were deemed important and/or where potential problems were expected are shown below in section 2.2.8.

2.2.8 Results and finding

Once the method and procedures had been conducted on all of the countries above, as well as on the continental/regional groupings, it was possible to analyze the outcomes and results obtained.

2.2.8.1 Predicted and Actual sedimentation rates

As stated previously, the procedure laid out in section 2.2.7.2 above was applied to each country/state and these sedimentation rates were used to project what the current (2006), as well as future, levels of sedimentation might be. From the summary of these results and the Sediment Yield Zones spreadsheet, charts were plotted along the continental/regional groupings. These charts appear below for Africa, Asia Australia and Oceania, the Middle East, North-, South-, and Central-America.

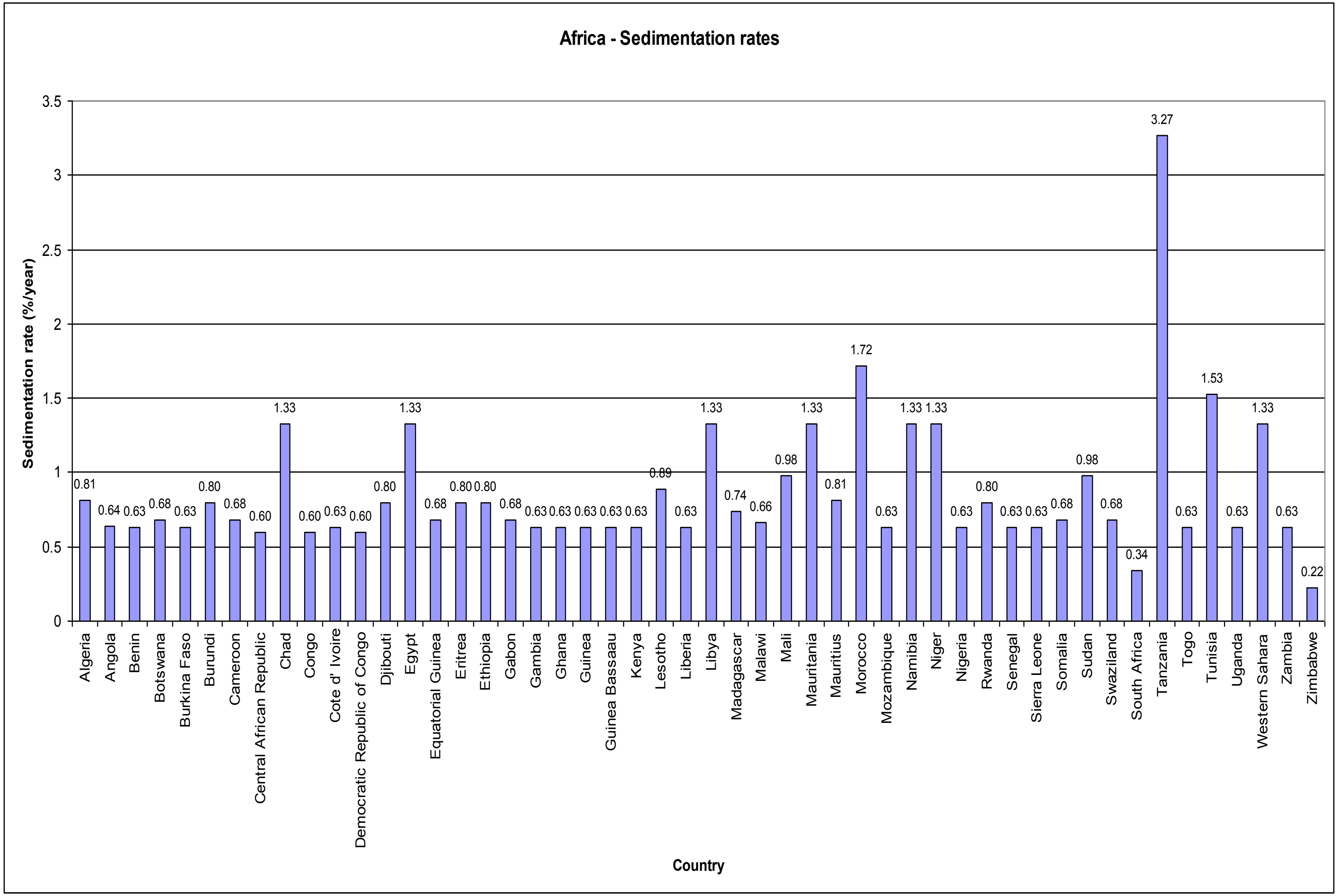


Figure 2.2-9 Actual and predicted sedimentation rates in Africa

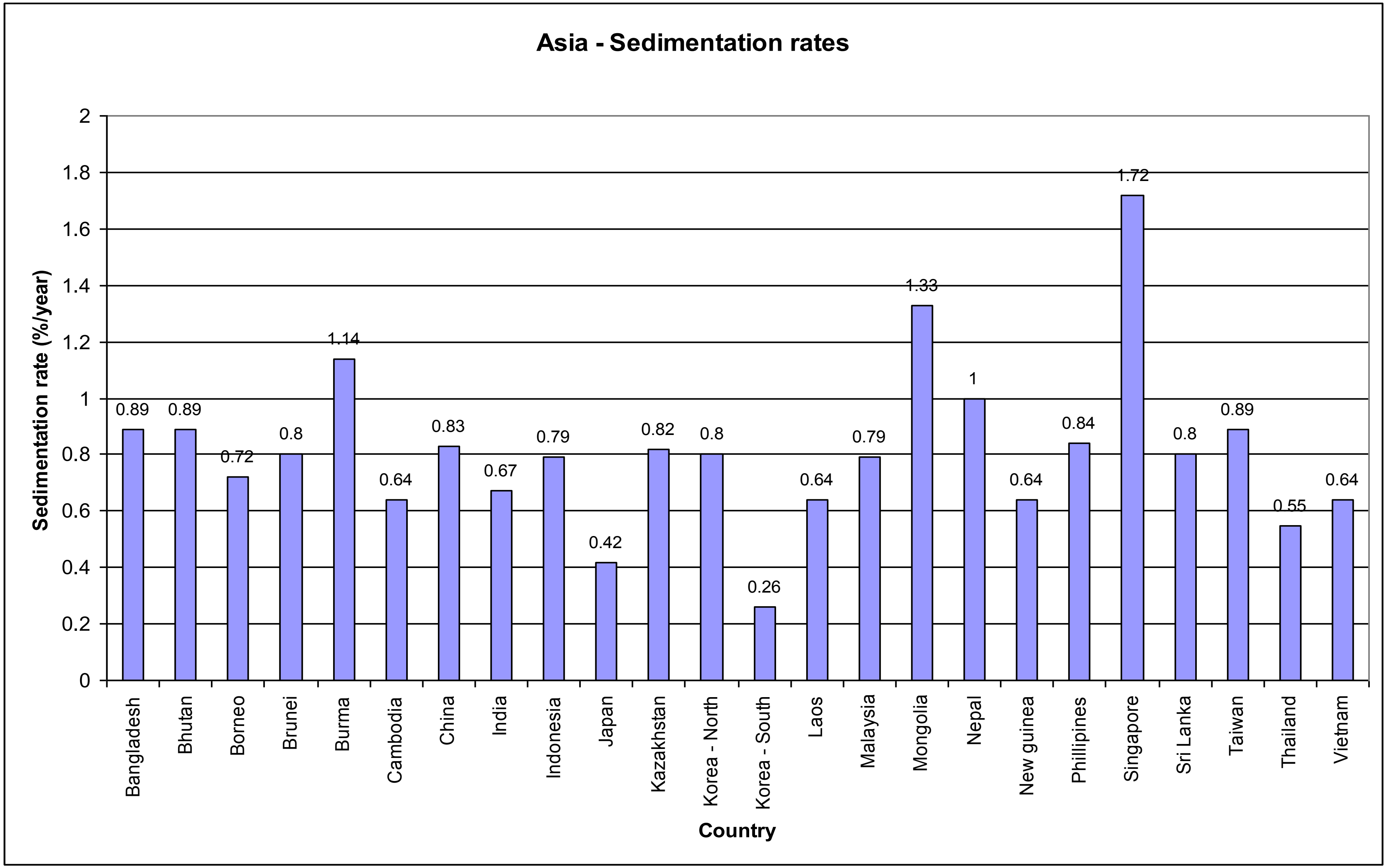


Figure 2.2-10 Actual and predicted sedimentation rates in Asia

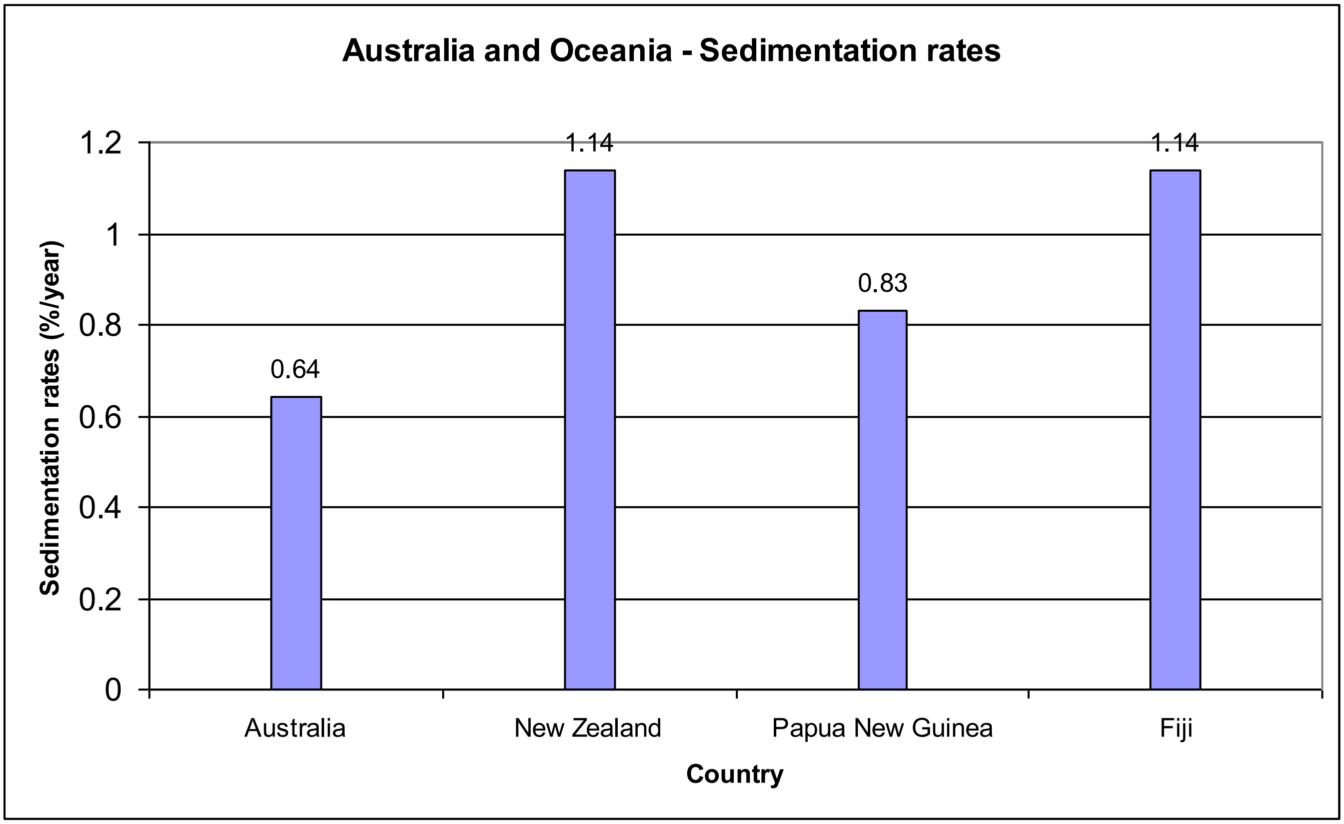


Figure 2.2-11 Actual and predicted sedimentation rates in Australia and Oceania

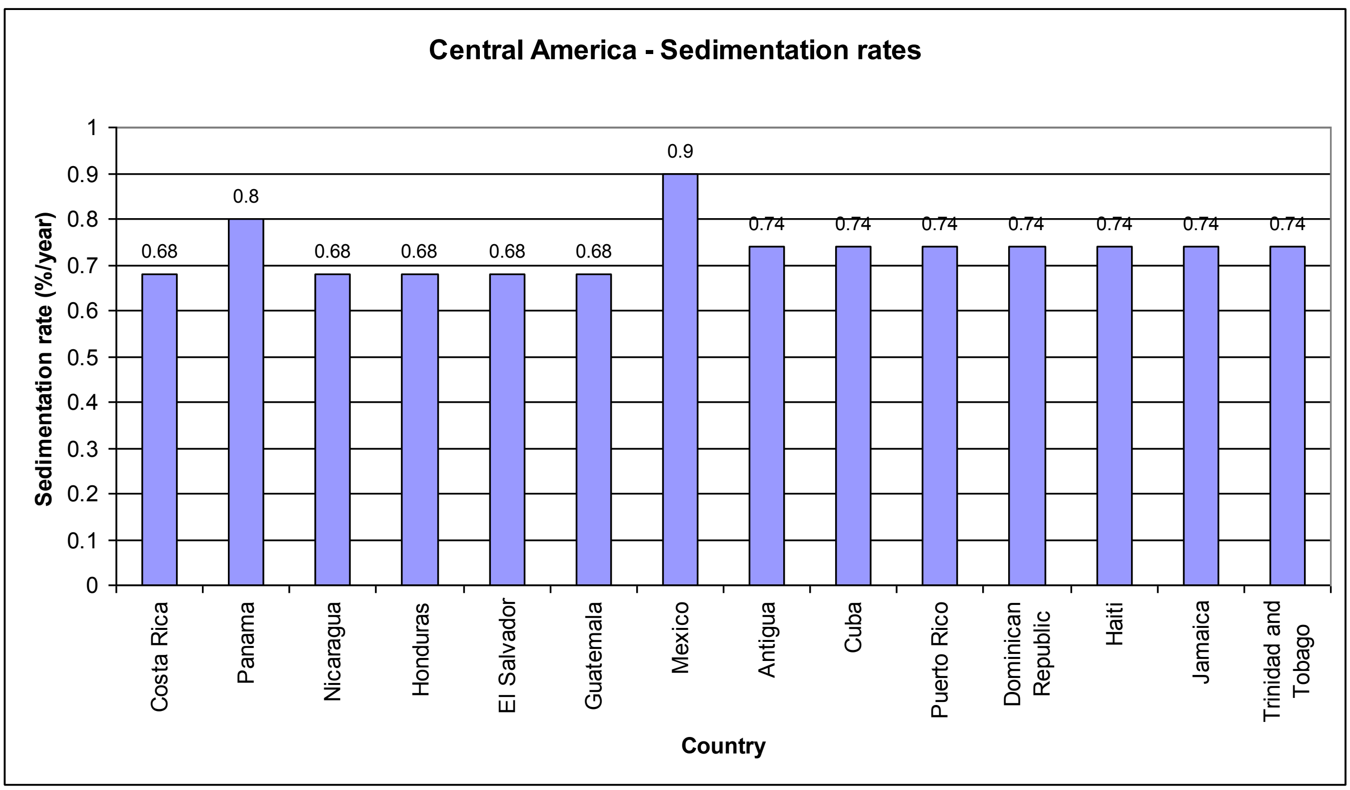


Figure 2.2-12 Actual and predicted sedimentation rates for Central America

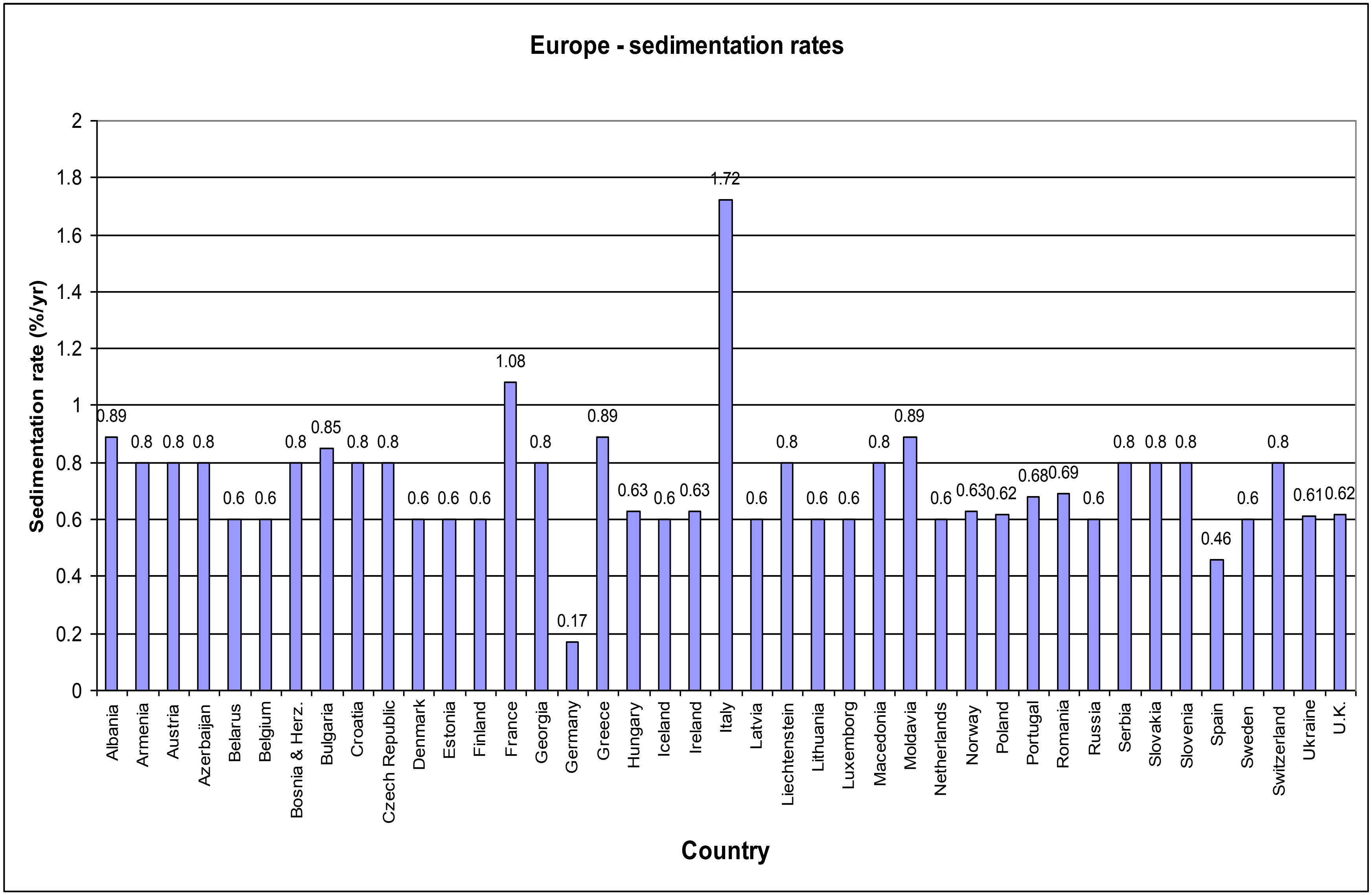


Figure 2.2-13 Actual and predicted sedimentation rates in Europe

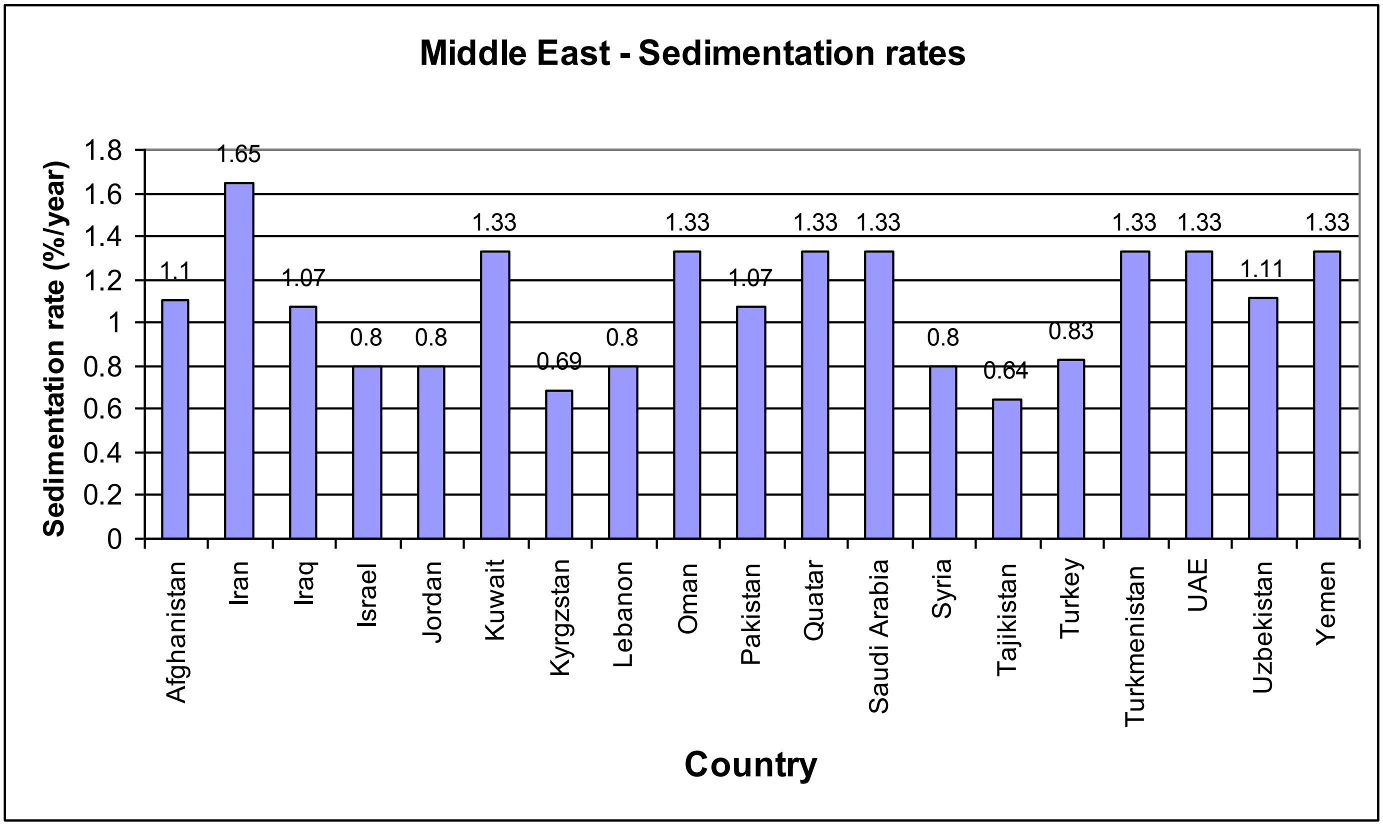


Figure 2.2-14 Actual and predicted sedimentation rates in the Middle East

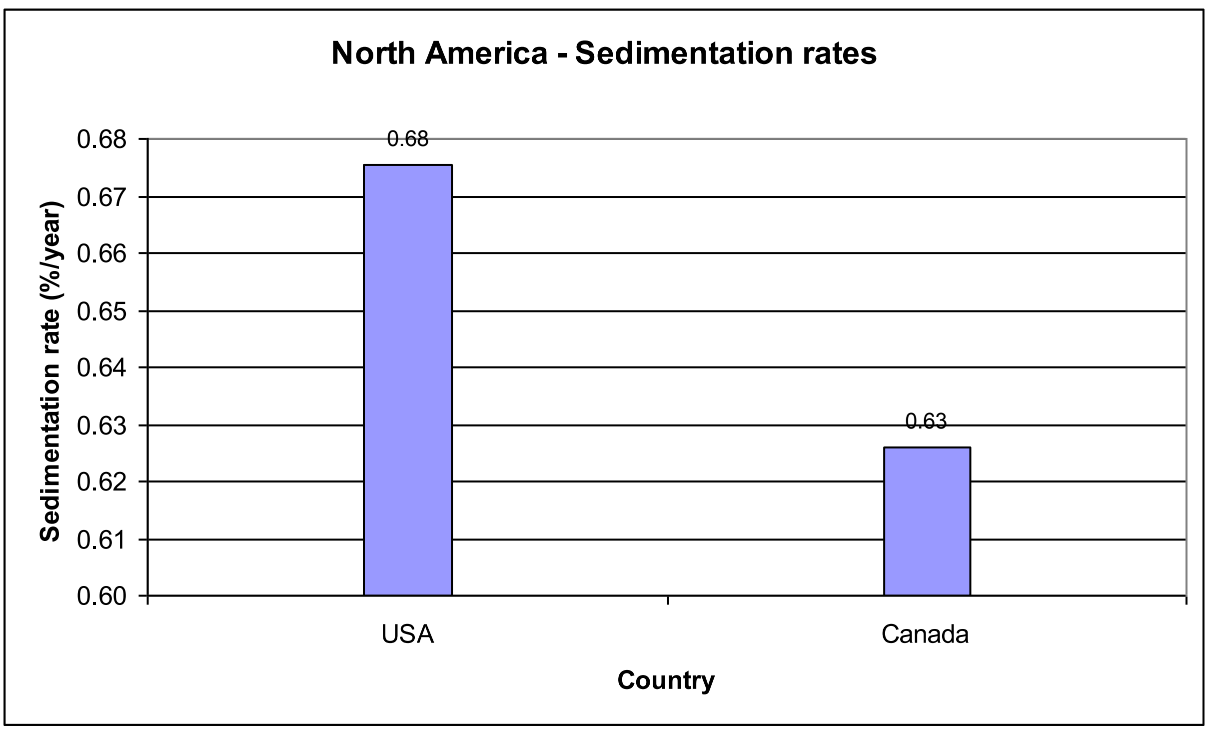


Figure 2.2-15 Actual and predicted sedimentation rates for North America

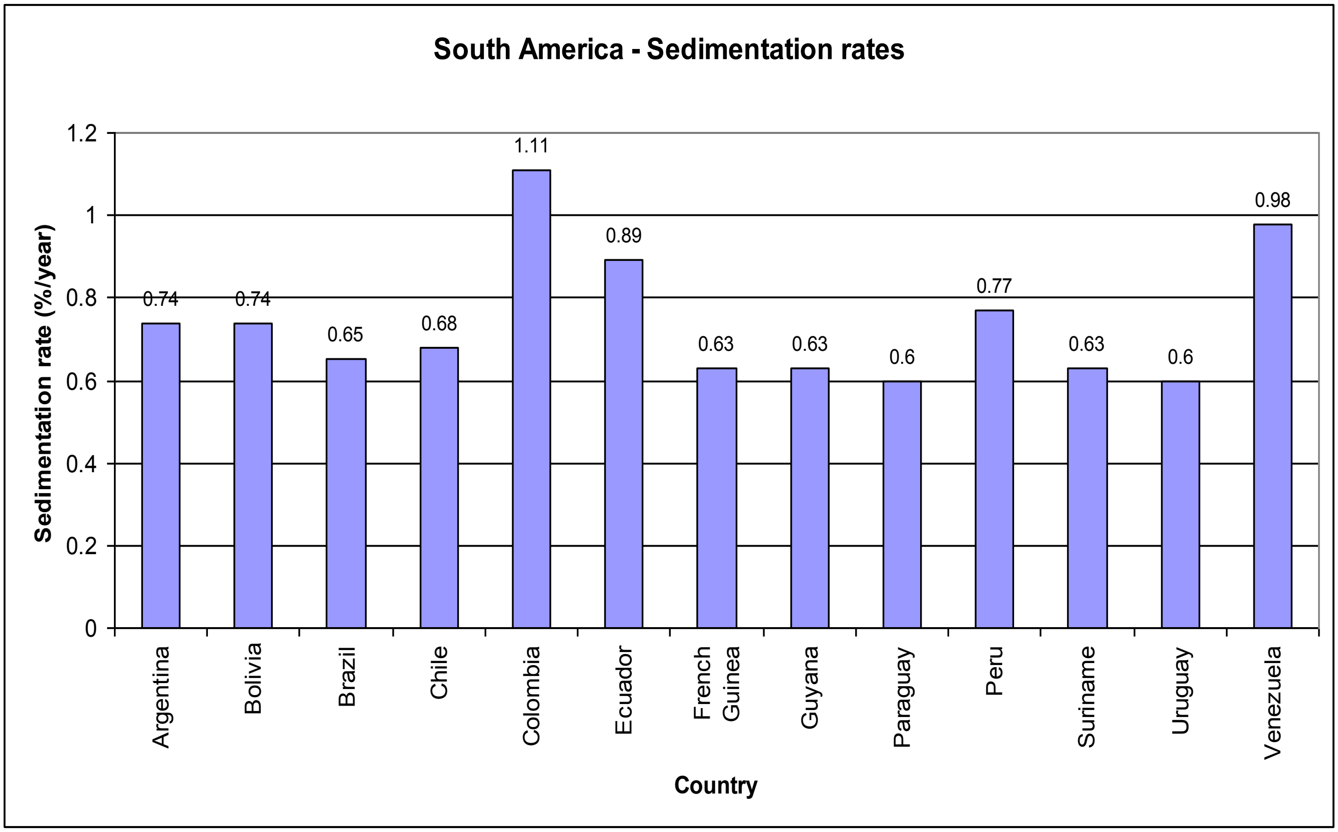


Figure 2.1-16 Actual and predicted sedimentation rates in South America

To show what the average sedimentation rate was for each region two approaches were used and the results are summarized below Table 2.2-13.

Table 2.2-13 : Average sedimentation rates for regions

Region	Average Sedimentation rate (%/year)	Weighted Average Sedimentation rate (%/year)
Africa	0.85	0.59
Asia	0.79	0.73
Australia & Oceania	0.94	0.74
Central America	0.74	0.86
Europe	0.73	0.65
Middle East	1.02	1.01
North America	0.68	0.68
South America	0.75	0.72

The Average sedimentation rate was calculated simply by obtaining the mean value from the values provided for each country, and were calculated by region. The weighted average sedimentation rate is obtained by:

1. Multiplying the total storage capacity of each country by the sedimentation rate (either predicted or observed).

2. The results of step 1. above are then summed together for all the countries in a given region.

3. The sum from step 2. above is then divided by the total storage capacity of the region. This gives the weighted average sedimentation rate.

This method of weighting the sedimentation rates was applied to take into account that some countries, for example China, Unites States of America, etc., have a much larger storage capacity, than Botswana or Uruguay, and thus, will contribute in a larger extent to the global average sedimentation rate.

In the article mentioned previously (Lempérière, 2006) it was stated that a rate of loss of storage of 0.3 %/year was a likely rate that should be expected globally. The sedimentation rates calculated using the method described in this Bulletin which is based on recorded data shows that on a regional level the average sedimentation rate is in no case less than 0.5 %/ year. Thus, the outcomes of this report seem to dispute the arguments put forward in the article above.

Using the data and methods above, a likely average sedimentation rate that could be called the global average is seen to be:

Average sedimentation rate	=	0.8 %/ year;
Weighted average sedimentation rate	=	0.7 %/ year;

This global rate, in both cases, more than doubles the rather low rate of 0.3 %/ year.

2.2.8.2 Predictions for crucial/important countries

The outcomes of applying the methods described in this Bulletin to the countries where detailed survey information was available will be discussed below, and are grouped by whichever region they belong to. To shorten this section only the crucial countries that could be experiencing major problems, or the ones where there was very detailed information will be discussed.

2.2.8.2.1 Africa

Data was available from 11 countries in Africa. From these countries the situation is by far the worst in Tanzania. The sedimentation rate for Tanzania was 3.27 %/ year. This value was obtained, as discussed, from the database of World Rivers and their sediment *yields* with the specific, single dam, which provided this rate being the Ikowa Dam. This is a small dam in Tanzania and does not appear on the World Register of Dams. Thus, though the situation seems bad because of this high sedimentation rate, the situation in the other reservoirs is probably not as bad as it seems.

2.2.8.2.1.1 South Africa

The graph for South Africa is shown below in Figure 2.2-17.

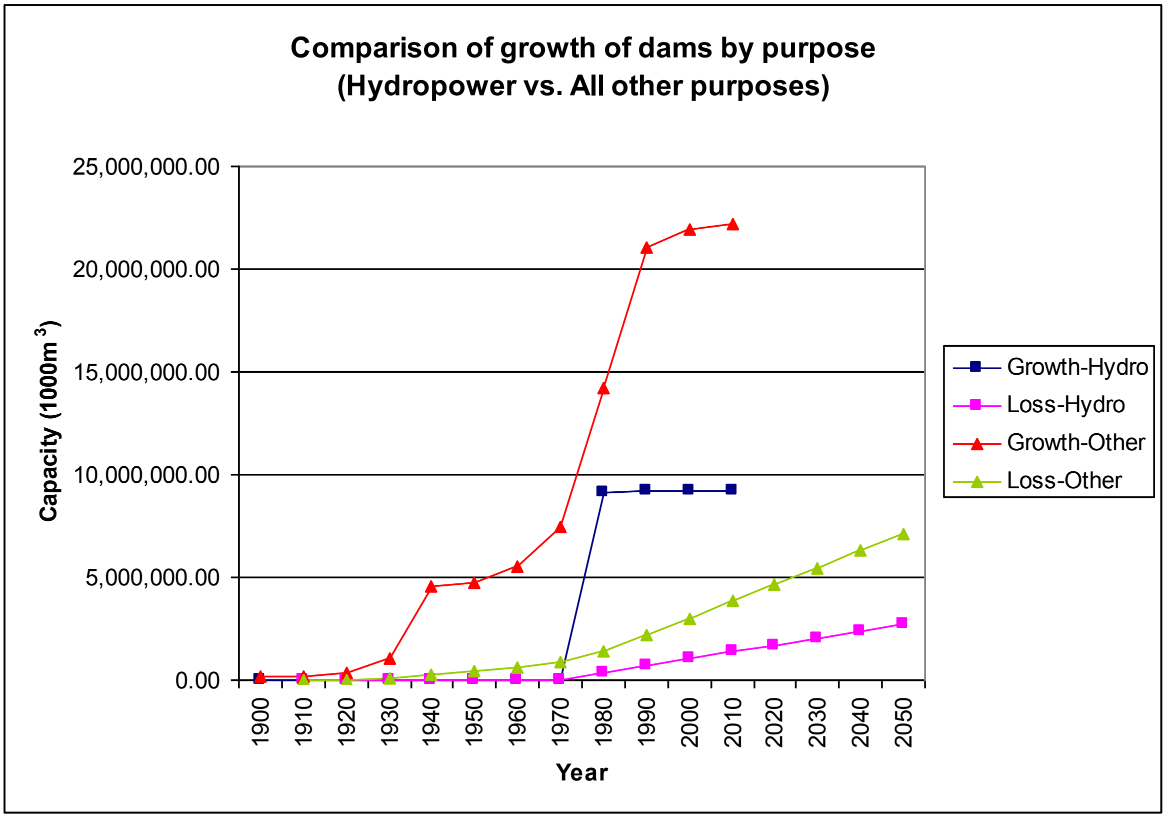


Figure 2.2-17 Comparison of growth of dams in South Africa

This chart shows that South Africa does not have many hydropower schemes and that the ones that are in place were completed prior to 1980. The sedimentation rate for South Africa is 0.37 %/ year and thus there are no short term problems predicted. Hydropower dams make up only 30 % of the storage capacity in South Africa.

2.2.8.2.1.2 Algeria

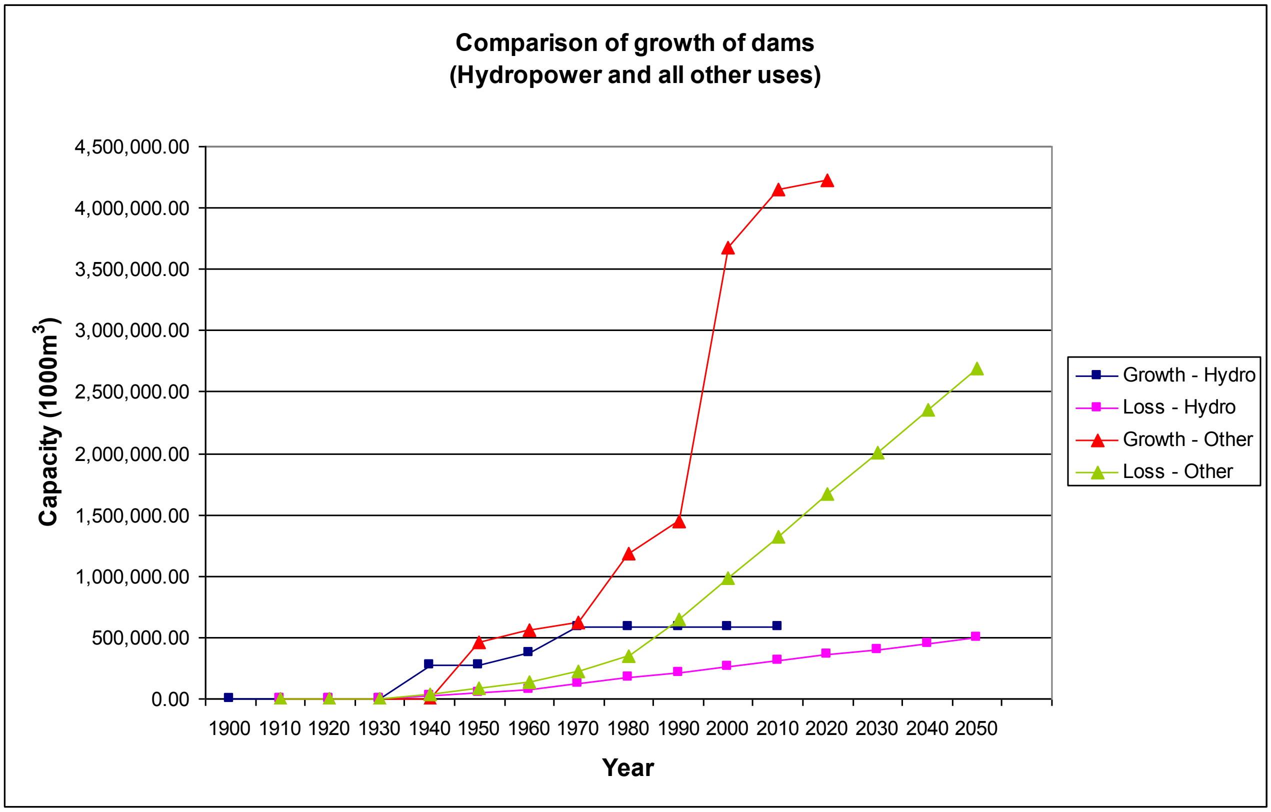


Figure 2.2-18 Comparison of growth of dams in Algeria

The graph for Algeria is shown above in Figure 2.2-18. It can be seen that no hydropower dams have been constructed in Algeria since before 1970. The sedimentation rate in Algeria is 0.81 %/ year and this means that for the last 30 years the Algerian hydropower storage capacity has slowly been depleted. The remaining percentage of hydropower storage is 46 %, and the predicted value in 2050 is only 14 % of the total hydropower storage capacity. The impacts on dams used for other purposes are not so large, as there has been continued construction over the years.

2.2.8.2.1.3 Morocco

Detailed information was also available for Morocco, and the graph comparing growth rates for reservoirs of different purposes is included below.

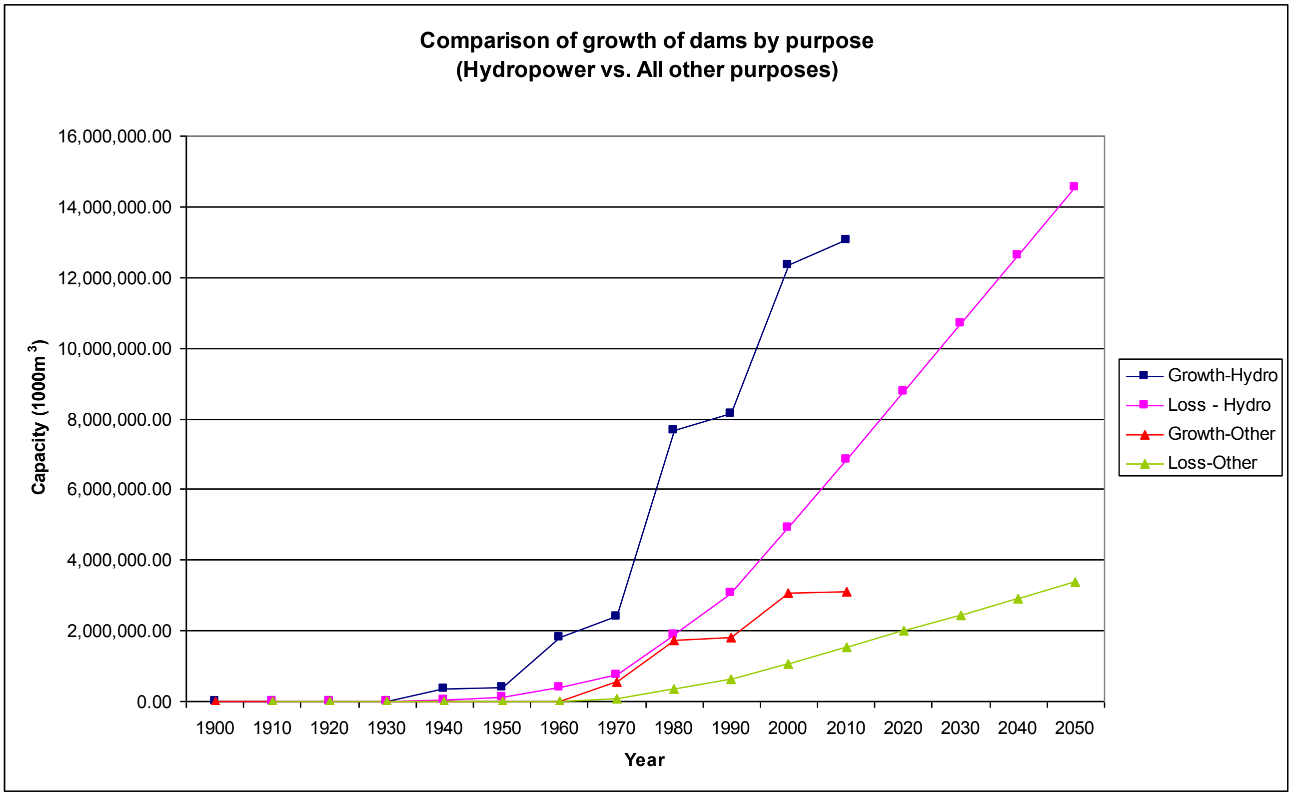


Figure 2.2-19 Comparison of growth of dams in Morocco

This graph shows that even though the sedimentation rate is high in Morocco the rate at which dams are being constructed is also still high, and this might ensure the sustainability of dams in Morocco for a while. However, if the rate of new dam construction slows, there could be major impacts on the storage capacity.

In 2006 the loss of storage capacity due to sediment build up was in the order of 52 % for hydropower and 49 % for all other purposes. This value was seen to increase and surpass the current total storage capacity for Morocco during the 2040's. This means, that if no further increases in total reservoir storage capacity occurs within the next 44 years that Morocco will have no storage capacity left by 2050.

2.2.8.2.2 Asia

2.2.8.2.2.1 China

China is considered to be the country with the highest number of dams. It was not deemed satisfactory to base the average sedimentation rate from the data that was available from 29 dams. Thus, it was decided to split China up by state and use the sedimentation yield zones to calculate the loss rates for each province as described in section. The results of this comparison are shown below on the graph.

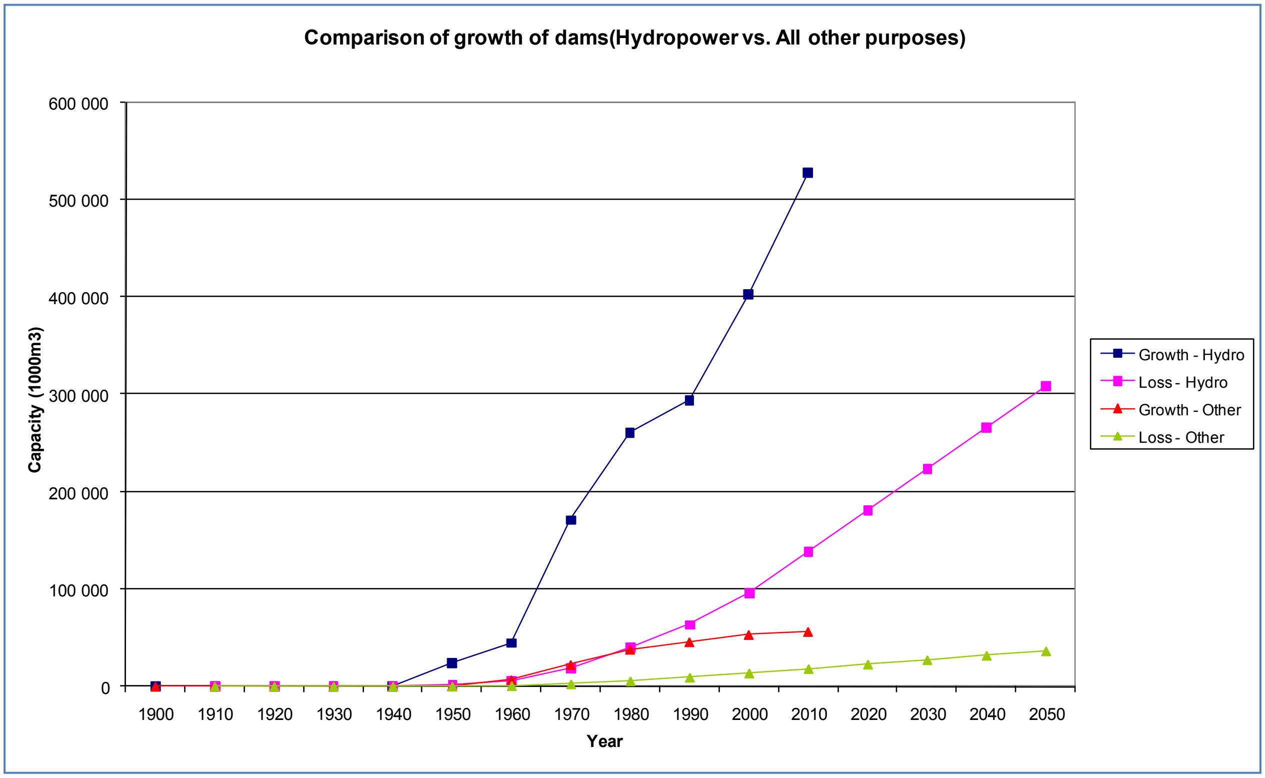


Figure 2.2-20 Comparing different sedimentation rates for China

If the sedimentation rate of 2.32 %/ year, as obtained from the data for 29 dams, is used for the calculations for China, China's current storage capacity will be completely filled by sediment within the next decade. In 2006 the remaining storage capacity is seen to be only 44 % of the total storage capacity. This rate seems to be extremely high, and it is probably not representative for most of the dams in China.

If the method as described is used, with the sedimentation rate calculated for each province then in 2006 the remaining storage capacity is seen to be 80 % of the total storage capacity. It is unclear whether or not either of these rates is correct, but the higher sedimentation rate cannot be assumed to be representative of a large majority of dams because it is much greater than the average global rate. Thus, in an attempt to represent most of the dams more accurately, it was decided to utilize the sedimentation rate, calculated province-by-province, for China.

The majority of dams in China are hydropower dams. It was seen that, by 2006, 26 % of the hydropower storage capacity had been filled with sediment and 32 % of the storage capacity for all other dam purposes had been filled. These figures are set to rise to 58 % and 65 % respectively, by 2050. The fact that China's sedimentation rate is potentially very high is negated by the very high rate at which dams are being constructed there.

2.2.8.2.2.2 India

The quality of information available and the research that has been conducted in India should be considered the benchmark, the standard to which other countries should strive. India was seen to have conducted extensive research and sedimentation surveys for various regions already, similar to what was performed in this report. The chart for India is provided below as Figure 2.2-21. In India, the majority of dams that are constructed are used for irrigation, but the hydropower dams are generally the larger dams, thus, there is more hydropower storage capacity than that for all other dam purposes.

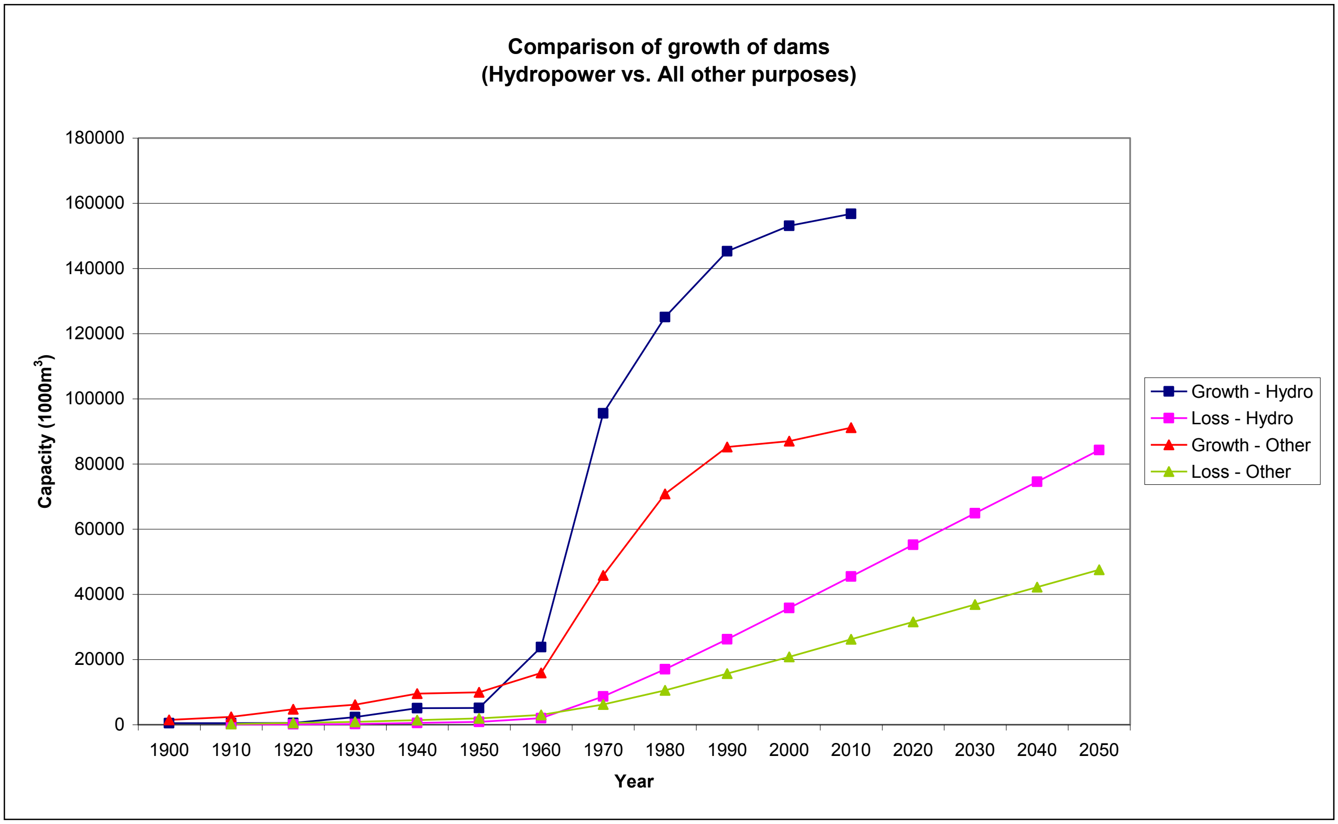


Figure 2.2-21 Comparison of growth of dams in India

The average sedimentation rate for India was found in to be 0.72 %/ year. However, the above graph was compiled by summing the graphs made (of the same type, comparing the growth of dams based on reservoir purpose) for each province, using each province's own sedimentation rate. If a province had no data collected from it, the sedimentation rate used for it was found by using the method based on what sediment yield zone that particular province lay in.

In 2006 the level of sedimentation is in the order of 29 % of the current total storage capacity for both hydropower and dams used for any other purpose. This value is predicted to increase to 54 % of the current total storage for Hydropower and 52 % of the current total storage for all other dam purposes by the year 2050.

2.2.8.2.2.3 Japan

Although the layout of the information might not be as presentable as that of India, Japan has the most current and largest database available. The surveys that were conducted were all done so in 2002 and in 2003 and these were done on 420 reservoirs. Considering that Japan is one of the smaller countries (in geographical size) that data was available for, it had the highest number of survey findings. However, from Figure 2.2-6 it was impossible to determine the sediment yield zone that Japan was in, and thus the sedimentation rate from Japan (probably the most accurate database) was not used in calculating the regional averages seen in Table 2.2-9.

The sedimentation rate for Japan is low, and thus no sedimentation problems are foreseen in the near future. Japan still has a high growth rate of storage capacity and this, coupled with the low sedimentation rate of 0.42 %/ year, means that Japan is showing good sustainable growth that is keeping slightly ahead of sedimentation.

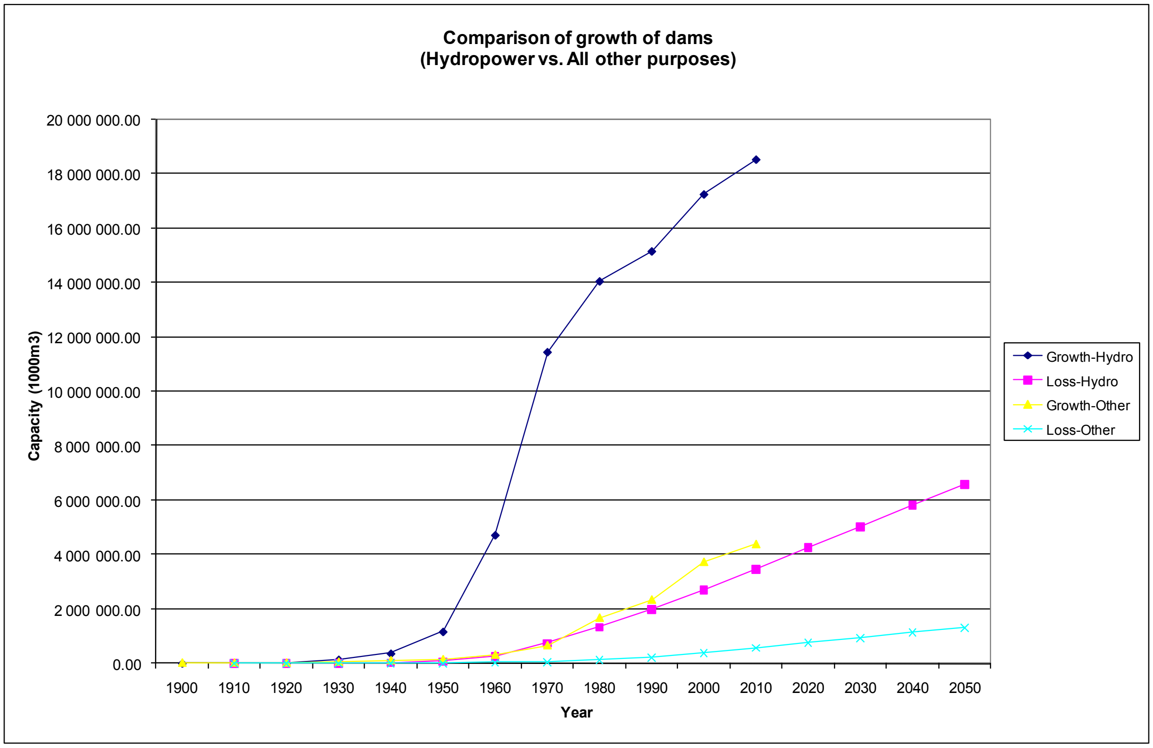


Figure 2.2-22 Growth of dams in Japan

2.2.8.2.3 Australia and Oceania

In this region the most critical country was seen to be New Zealand. The sedimentation rate that was the average from 5 reservoirs was seen to be 1.14 %/ year. This is a relatively high sedimentation rate and is illustrated on Figure 2.2-23.

The bulk of the storage capacity in New Zealand is made up of Hydropower dams. The boom in construction was seen in the 1970's, and since the 1990's there has been practically no dam building in New Zealand.

For hydropower the level of sedimentation is 51 % of the total current storage capacity. This value will increase to 96 % of the current total supply capacity by 2050. The situation is similarly bad for all other dam purposes.

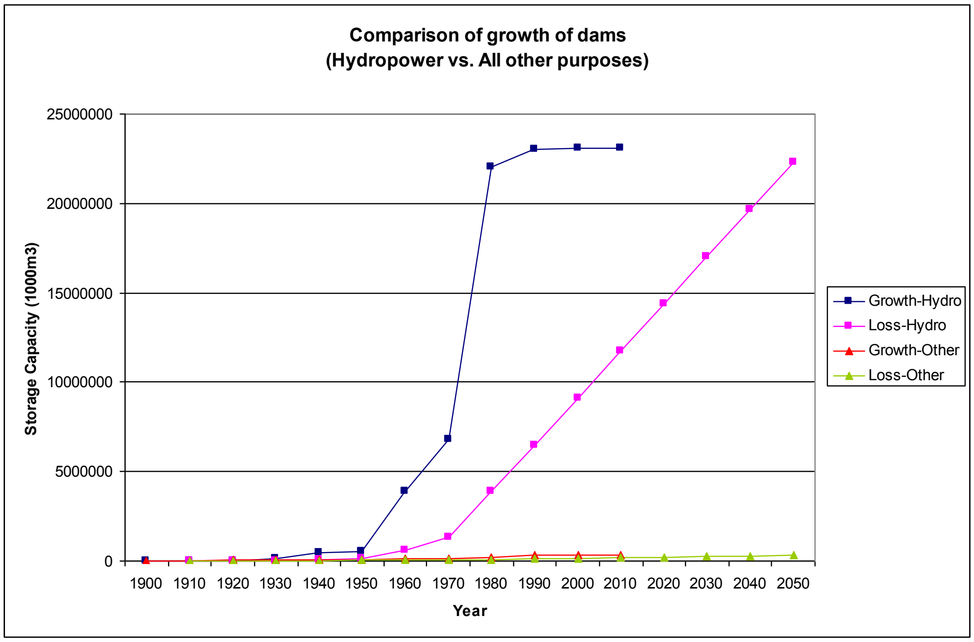


Figure 2.2-23 Comparison of growth of dams in New Zealand

2.2.8.2.4 Central America

The only country in this region that had information available was Puerto Rico, and this data showed that the sedimentation rate was 0.74 %/ year. The growth curve is shown in Figure 2.2-24.

For hydropower there has been no dam construction since the 1960's and this means that there has only been a decreasing storage capacity since the 1960's. The proportion of the total current storage capacity lost by 2006 is, for hydropower, 52 % which will increase to 81 % by 2050. For all other dam purposes, in 2006, 39% of the total storage capacity has been lost, set to increase to 69 % by 2050.

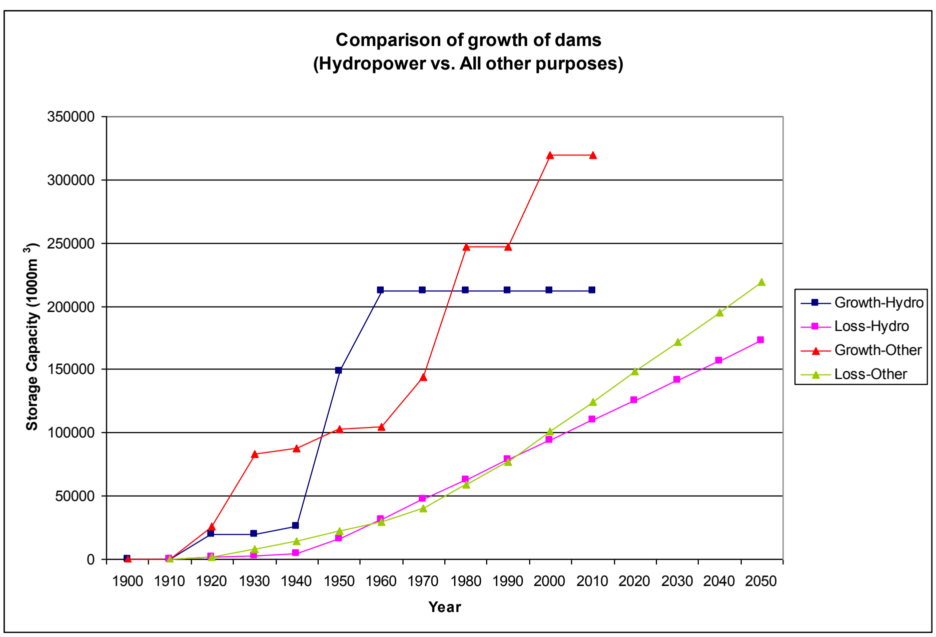


Figure 2.2-24 Comparison of growth of dams in Puerto Rico

2.2.8.2.5 Europe

2.2.8.2.5.1 France

The sedimentation rates that were available from Europe were generally lower than the average sedimentation rates for the world as a whole, except for the rate seen from France, which was found to be 1.08 %/ year. The situation for France using this sedimentation rate is shown as Figure 2.2-25 below.

For both hydropower and dams for all other purposes there has been almost no new dam construction since the 1990's. For all other purposes, besides hydropower, it is expected that 48 % of the total storage capacity will have been lost by 2006, with this value increasing to 91 % of the current total storage capacity by 2050.

For hydropower by 2006 the loss of storage capacity was seen to be 50 %, with this value rising to 93 % of the current total storage capacity by 2050.

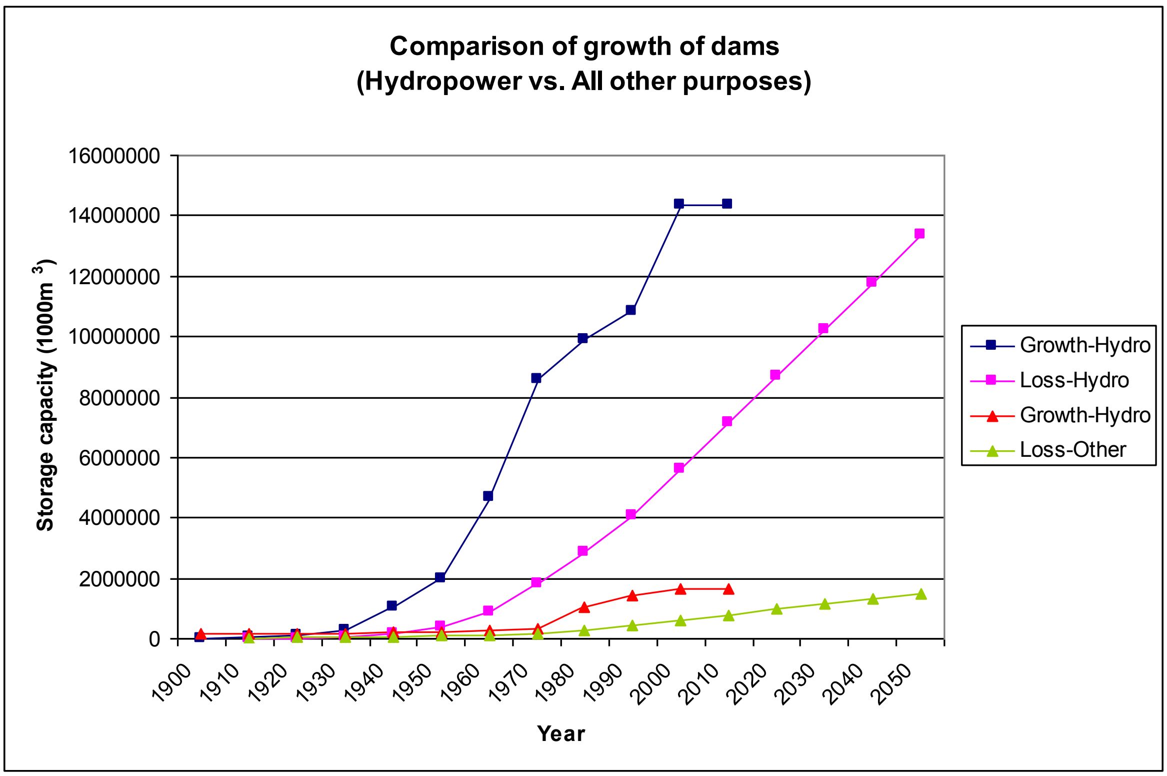


Figure 2.2-25 Comparison of growth of dams in France

2.2.8.2.5.2 Italy

Figure 2.2-26 shows the graph for Italy. The average sedimentation rate is estimated at 0.25% per year. Most of the dams are located in the north of Italy in the Alpine region where the sedimentation rate is about 0.15%/year. In other areas of Italy sedimentation rates of 0.68 to 0.8% per year has however been reported.

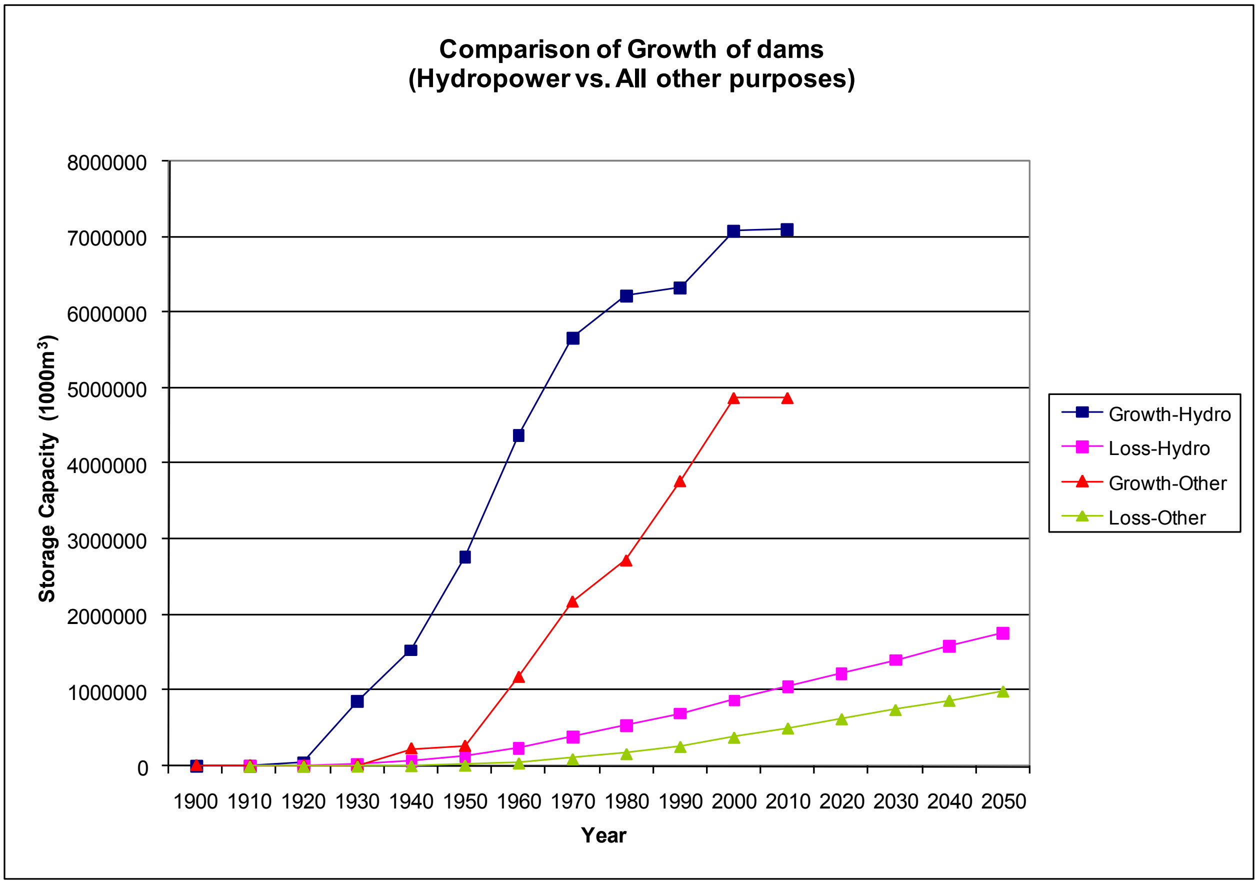


Figure 2.2-26 Comparison of growth of dams in Italy

It is expected that Italy's Hydropower storage capacity will be depleted by 25% by 2050 in Italy. For dams for all other purposes by 2050 about 20% of the total storage capacity would be depleted by sedimentation.

2.2.8.2.5.3 Russia

Russia has relatively few dams appearing on the World Register, when one considers the size of the country. It was, however, seen that the dams present were all very large dams 14 862 million m^3 being the average storage capacity for the dams present. This was seen to be the highest value for any country. It was also noted that the majority of these dams were built for hydropower generation. This can clearly be seen in Figure 2.2-27 below. There was no data provided for Russia, so the rate was predicted using the method described earlier.

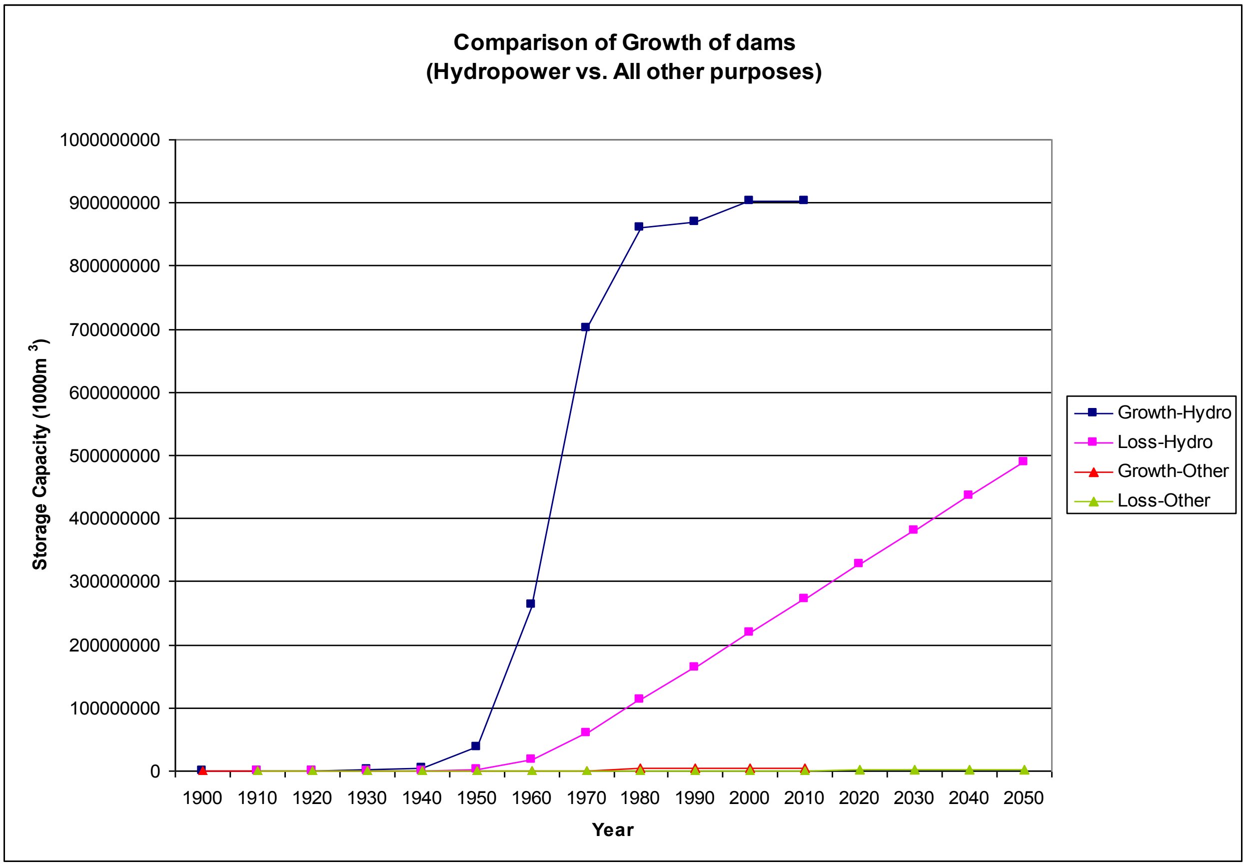


Figure 2.2-27 Comparison of growth of dams in Russia

It was seen that the predicted sedimentation rate of 0.6 %/ year means that this large storage capacity will be relatively free of sedimentation problems. By the year 2050, for Hydropower dams, 51 % of the storage capacity would have been filled with sediment. This value is lower than that seen in most countries.

2.2.8.2.6 Middle East

There was only data available for Pakistan and for Iran from this region. Of the two of these countries, Iran was seen to have the worse sedimentation rate, of 1.65 %/ year. The graph for Iran is shown below as Figure 2.2-28.

Iran is seen to exhibit a high growth rate of storage capacity for all purposes of dams. The boom in dam construction for Iran started later than is typically seen, and the current rate of increase is the most rapid seen for any country. The sedimentation rate is high, but if Iran can build new dams that incorporate sluicing, and other new methods of lowering the trapping efficiency into the design then the situation could be neutralized.

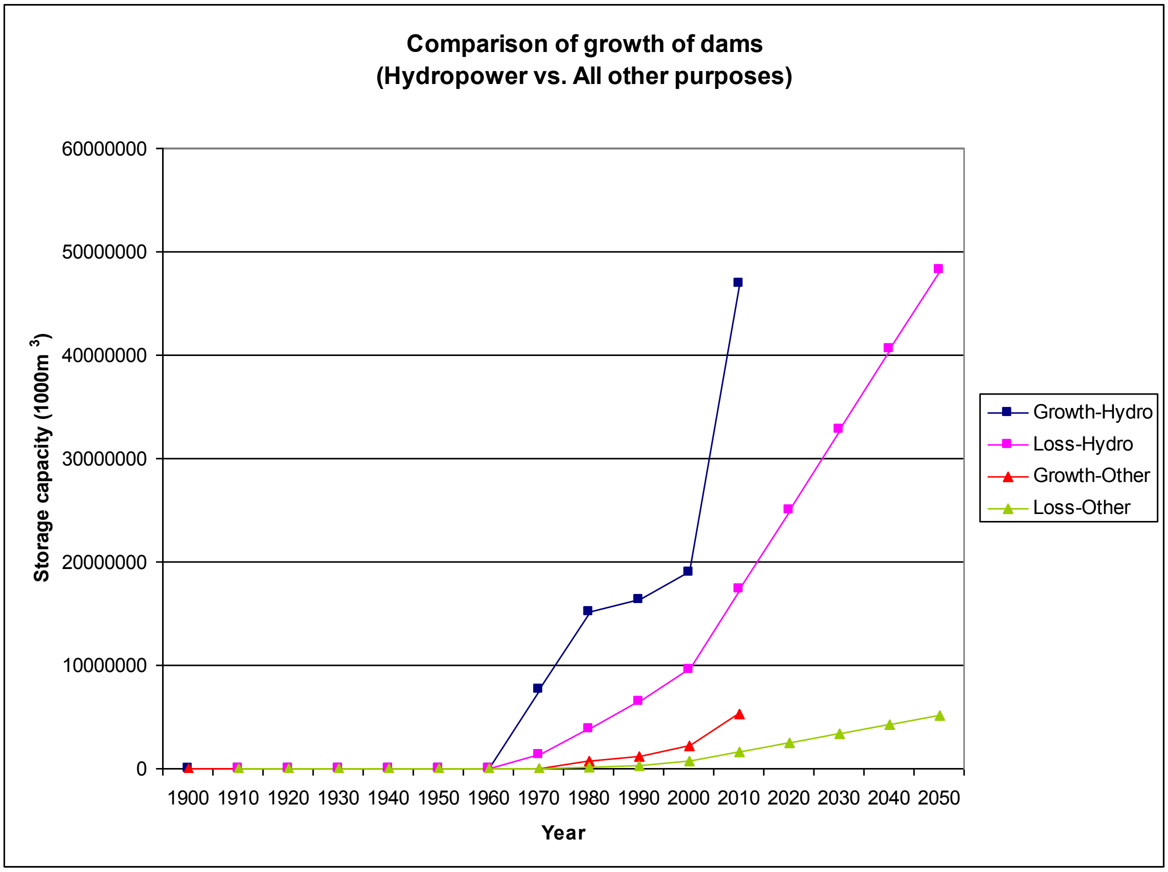


Figure 2.2-28 Comparison of growth of dams in Iran

2.2.8.2.7 North and South America

For North America, it was seen that the capacity of dams in Canada was disproportionately large. It was seen to be the same magnitude as the sum of all other dams in the world. On closer inspection it seems as though there are values repeated numerous times that have been included in the World Register on Dams. It was decided to leave Canada out of any further part of this study, because of the doubt involved. To show the results obtained, using the methods laid out in this report, the graphs for USA and for Brazil are given below.

2.2.8.2.7.1 United States of America

As stated previously, data for America was only available from seven of the States of America. These values were used for the respective States, and the unknown values were predicted using the method put forward above. To plot the curve, the data was summed for all the States to represent the whole country, as shown below in Figure 2.2-29 with the units of million m^3.

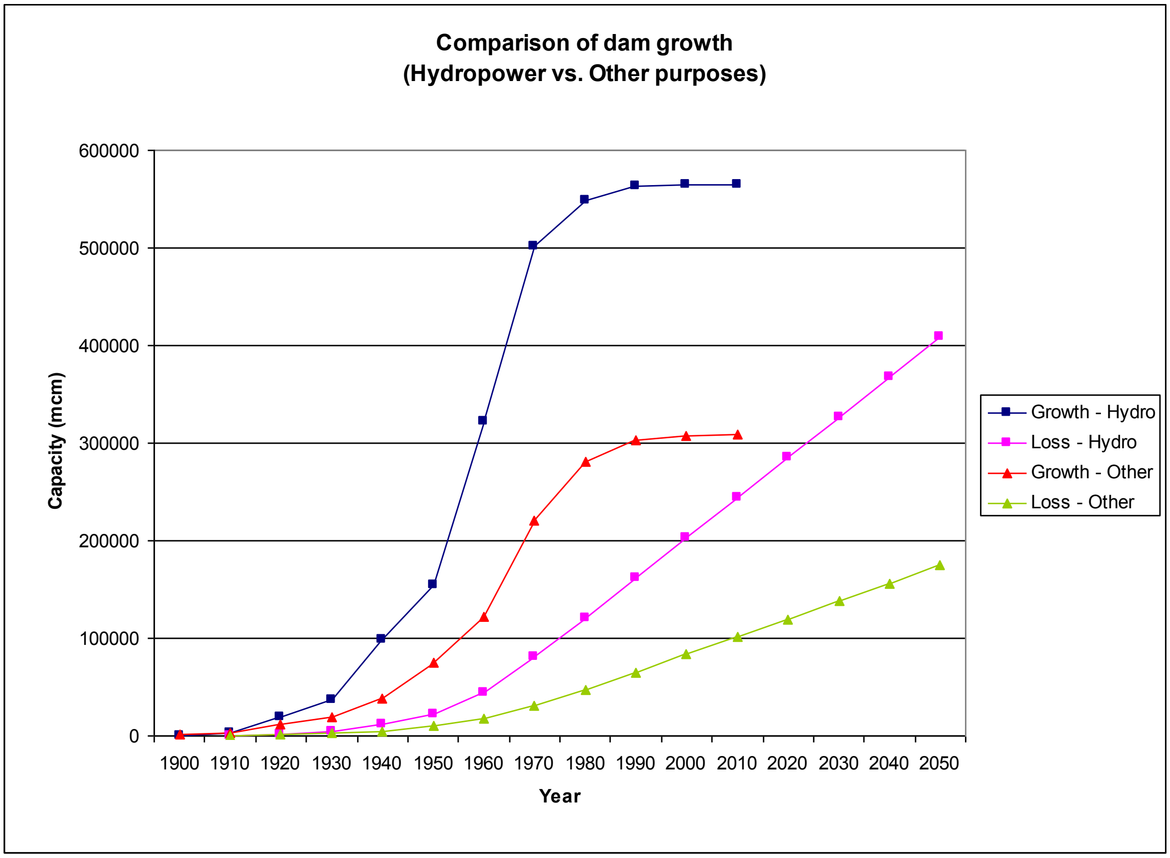


Figure 2.2-29 Comparison of growth of dams in USA

Unlike most countries, dams for purposes other than hydropower make up just over one third of the total storage capacity. As stated in earlier, the results using this method seem to show an over-estimation of the sedimentation rates in America. These over-estimated rates already show that sediment accumulation is not a pressing area of concern in America, as it is in other parts of the world.

2.2.8.2.7.2 Brazil

No data could be obtained for Brazil. The method, as stated in earlier, was applied to each province separately. Figure 2.2-30 was plotted using the cumulative data and appears as seen below.

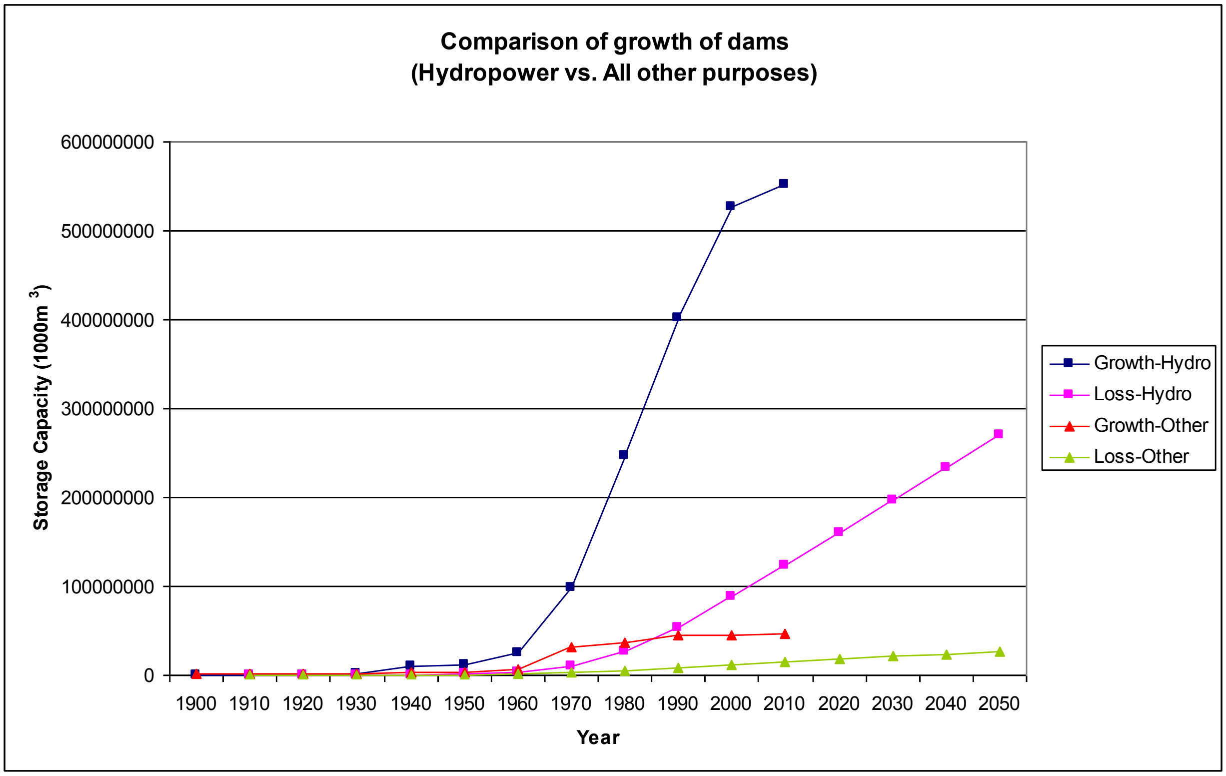


Figure 2.2-30 Comparison of growth of dams in Brazil

The curve shows that dam construction, for Hydropower is still going forward in Brazil at present. The sedimentation rate appears to be very low, and thus no problems are expected for the Hydropower storage for numerous years. Construction of all other purpose dams stopped before 1990, and thus there could potentially be problems for these dams. In 2006 the expected volume lost to sediment is 31 %, and this will increase to a value of 58 % by 2050.

2.2.8.3 Growth of storage capacity for regions

As seen in Figure 2.2-8 above the cumulative growth and loss curves over time were calculated for each country. These were then summed together to produce the curves for the region as a whole. These curves are attached below as Figure 2.2-31 through to Figure 2.2-38. The units for these graphs are expressed as "mcm" which stands for million cubic meters or 10^6 m^3.

2.2.8.3.1 Africa

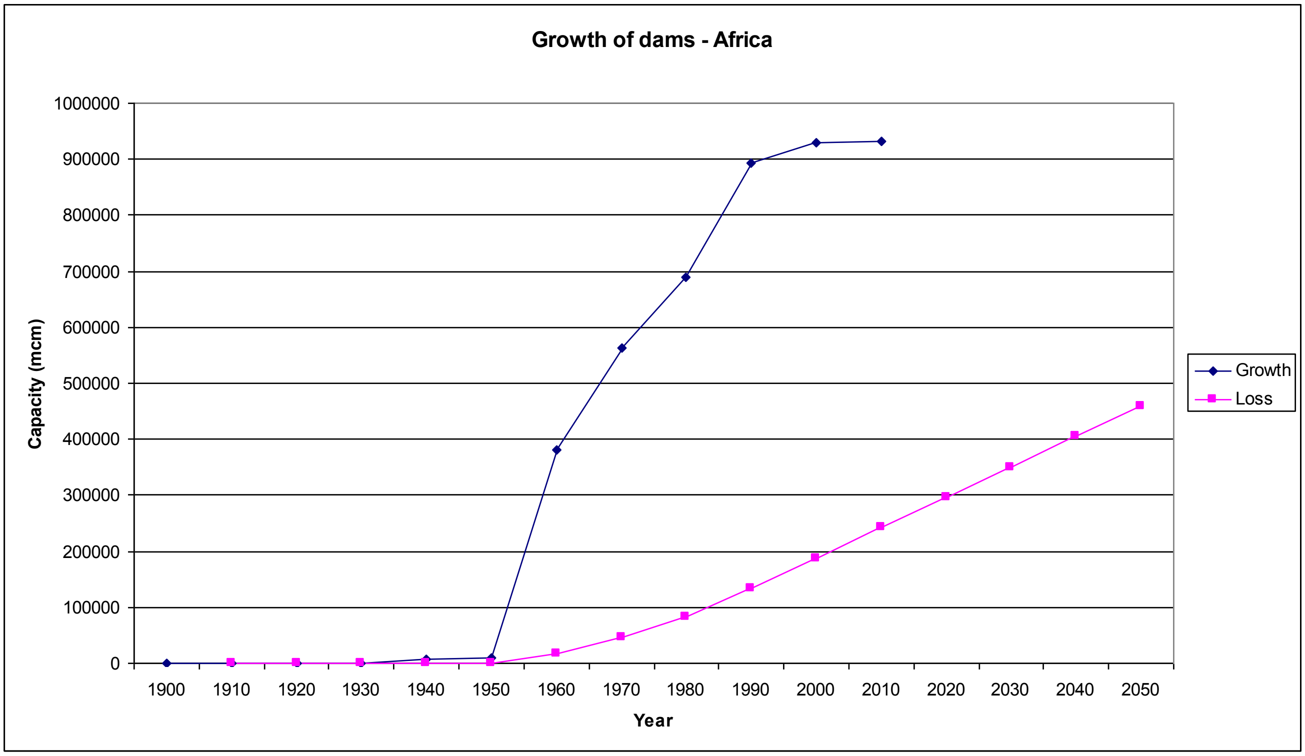


Figure 2.2-31 Growth of Dams – Africa

Figure 2.2-31 shows that dam construction started in earnest in the 1950's in Africa. The growth rate was still high but was slowing down through the 1960's and 1970's. There was another surge in the growth rate in the 1980's with a decreasing rate of growth from then through to the present. The total storage capacity for Africa in 2006 is approximately 932 000 mcm.

By 2006 it was calculated that the remaining storage capacity was roughly 81 % of the theoretical full supply capacity, which represents an accumulation of sediment of 19 % of the total capacity. This relates to a volume of sediment of approximately 178 000 mcm.

By 2050, the sediment accumulation would have increased to 44 % of the total storage capacity, leaving only 56 %, or 523 000 mcm.

2.2.8.3.2 Asia

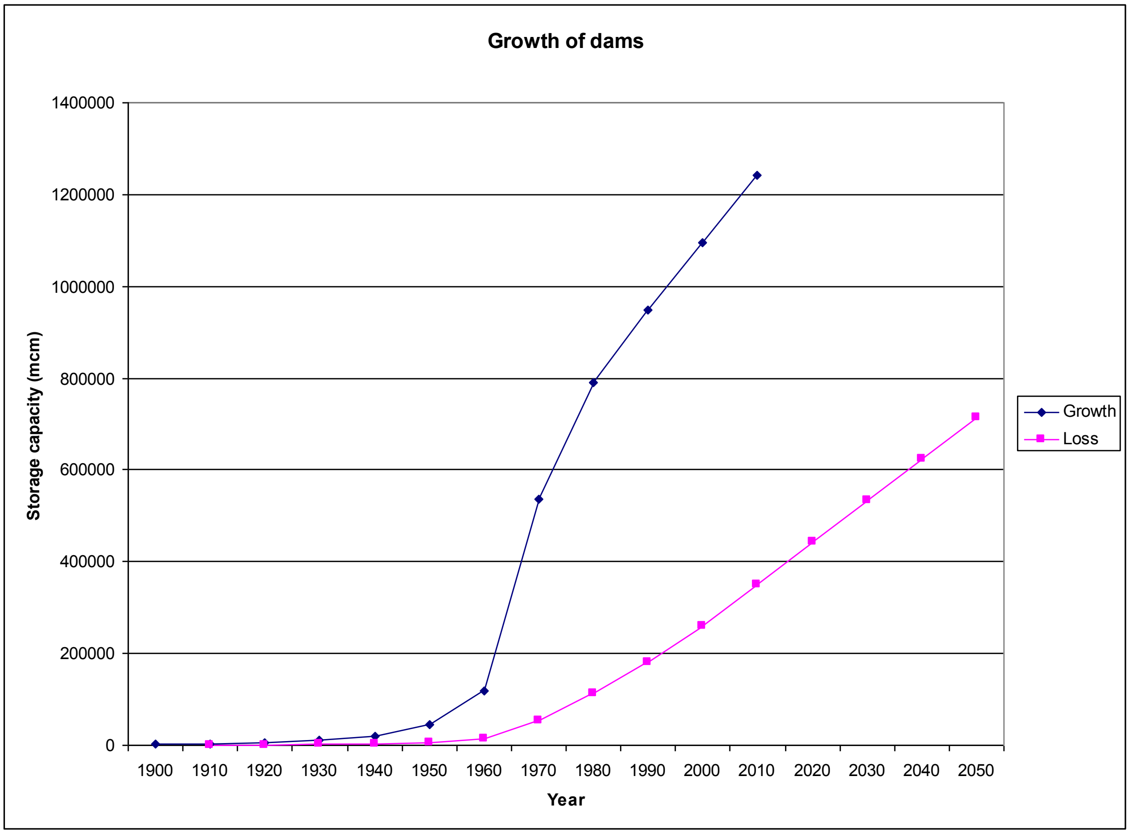


Figure 2.2-32 Growth of dams – Asia

The image for Asia, as shown above in Figure 22-32, is one of high dam growth from the 1960's that continues right on till the present. The rate of increase has slowed since the initial boom, but unlike most of the other regions there seems to be no slowing down. This large growth rate can be mainly attributed to China, which continues to build large dams (e.g. the Three Gorges dam, due for completion in 2009) at a relatively fast rate.

The total capacity of storage for Asia is 1 242 000 mcm, and at present (2006) it is estimated that roughly 80 % of that storage capacity is free of sediment. There has been approximately 252 000 mcm of sediment accumulated at present. By 2050, however, almost 53 % of the current total storage capacity would have been lost to sediment, correlating to a volume of approximately 652 000 mcm.

2.2.8.3.3 Australia and Oceania

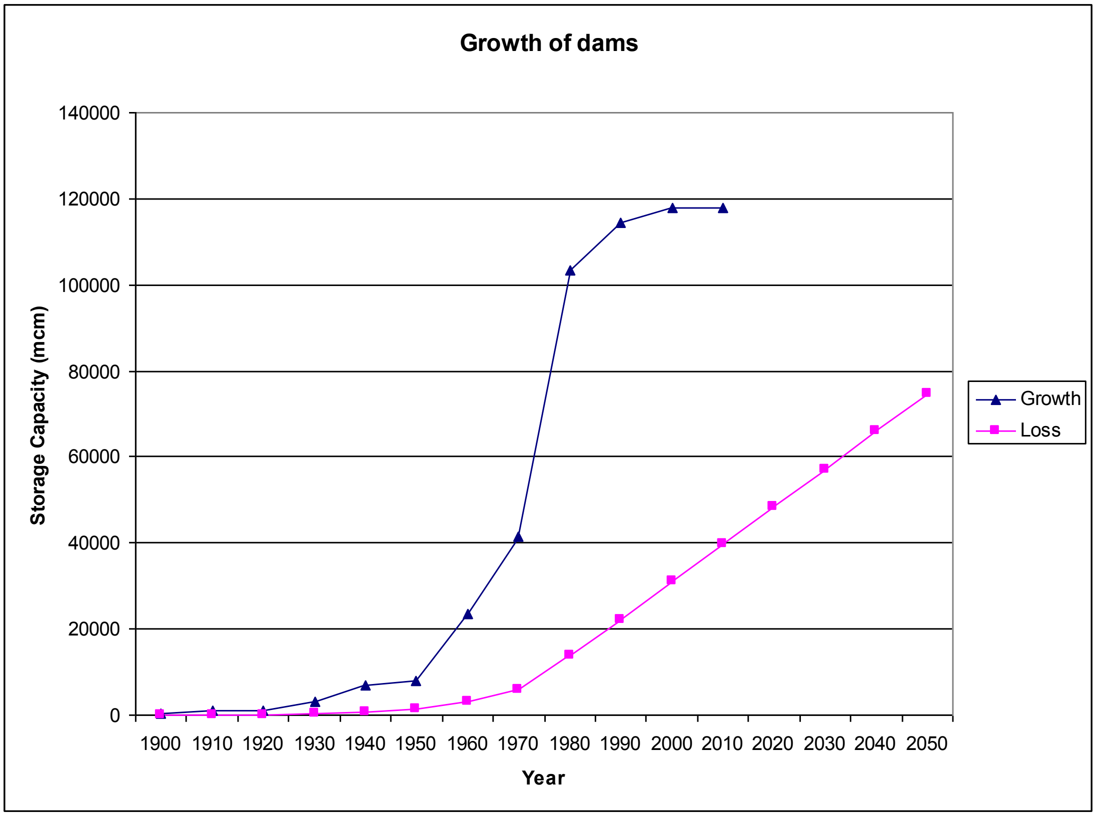


Figure 2.2-33 Growth of dams - Australia and Oceania

Relatively early growth of dam capacity was seen starting in the 1920's, but with the major boom beginning in the 1950's. From 1980 onwards there has been little or no large dam construction. (See Figure 2.2-33 above.)

The total storage capacity for this region is almost 118 000 mcm in 2006. By 2006 the loss of storage capacity due to sedimentation has resulted in 73 % of this total capacity being free of sediment.

The volume of sediment that has accumulated at 2006 is 32 000 mcm or 27 % of the total storage capacity. By 2050 this volume of sediment would have increased to 70 000 mcm leaving only 41 % of the regions current total storage capacity free of sediment.

2.2.8.3.4 Central America

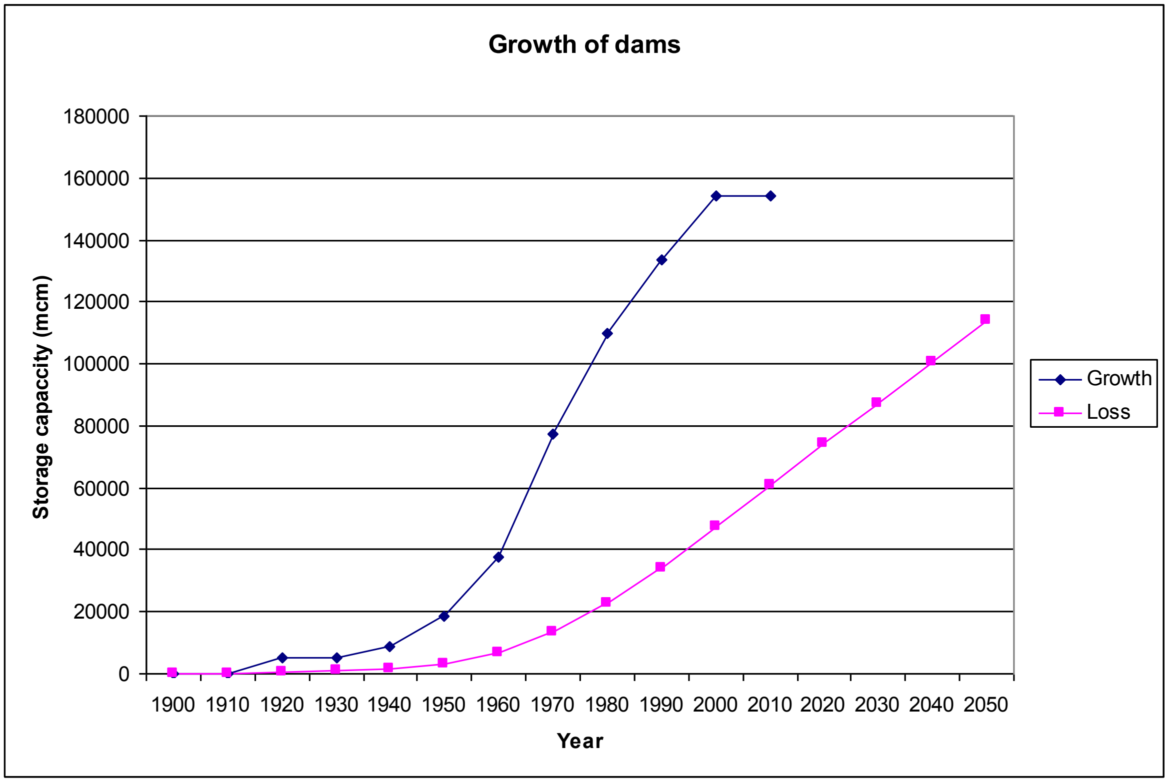


Figure 2.2-34 Growth of dams - Central America

Dam construction started relatively early in Central America as well, and reached its peak growth rate during the 1960's. There was a steady increasing rate of capacity, until the beginning of this century (2000) and since then there have been few dams constructed. (See Figure 2.2-34 above.)

The total storage capacity in 2006 for Central America is in the order of 154 000 mcm. Currently the storage capacity free of sediment is 104 000 mcm, or 68 % of the total storage capacity.

The volume of sediment accumulated thus far, is 49 000 mcm, which will continue to increase to a value of 107 000 mcm from now till the year 2050. The remaining proportion of the current storage capacity left at 2050 will be only 31%.

2.2.8.3.5 Europe

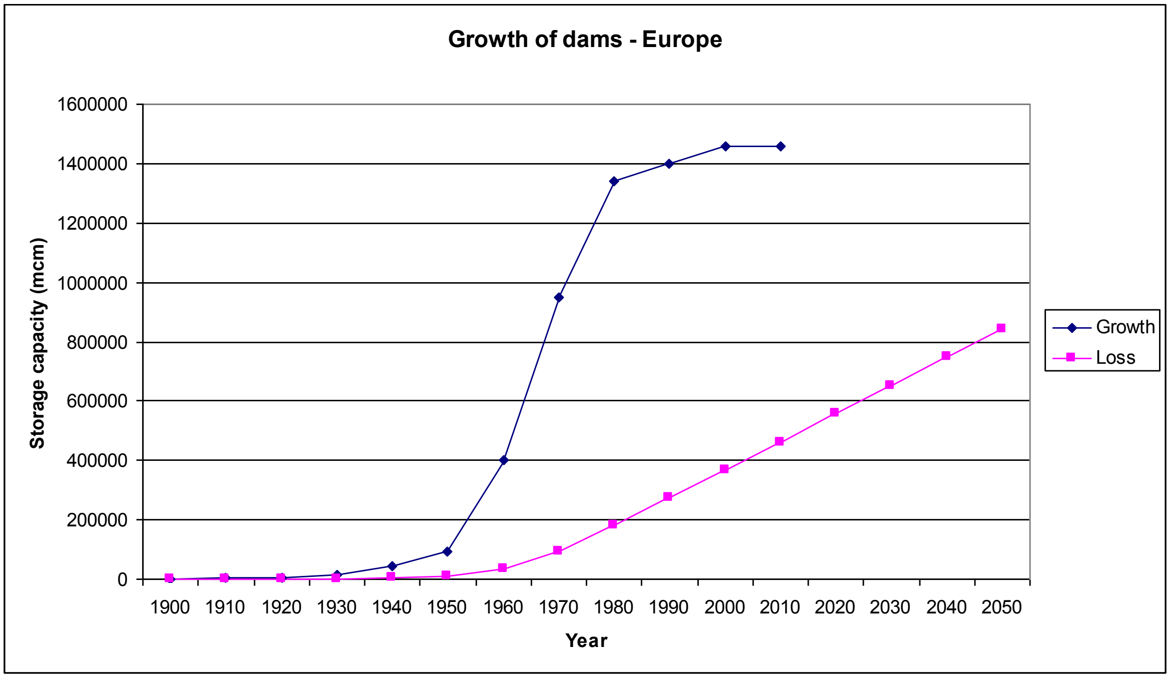


Figure 2.2-35 Growth of dams – Europe

Europe shows the typical tendency of a boom in dam construction in the 1950's through to 1980; followed by an ever decreasing rate until 2000, thereafter no significantly large dams have been constructed.

The total storage capacity for Europe is 1 461 000 mcm, with sediment accumulation resulting in the available storage capacity in 2006 being 1 077 000 mcm, which is 74 % of the potential storage capacity. The volume of sediment in 2006 of 384 000 mcm will increase over the next 44 years so that in 2050 it will be 796 000 mcm. This represents almost 55 % loss of the total storage capacity.

2.2.8.3.6 Middle East

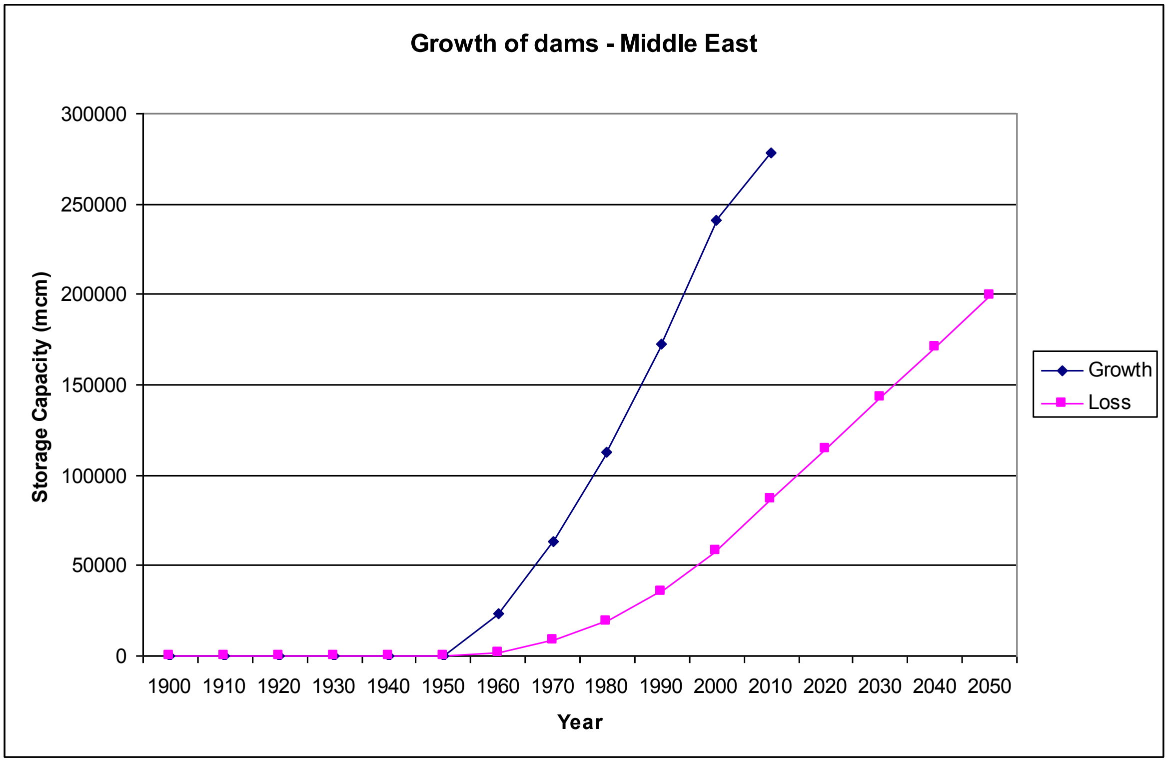


Figure 2.2-36 Growth of dams - Middle East

The growth curve for the Middle East, Figure 2.2-36, is seen to be set later in time than other regions. The boom in construction generally occurred in the 1950's or 1960's, however, for the Middle East it is seen to have really started in the 1970's. There has been a slight decline in the growth rate, but construction is still going on a larger scale than in most other regions. This is seen, for example, in Iran which is currently said to be constructing dams at the fastest rate for any country in the world.

However, according to Table 2.2-36 above, the Middle East has the highest sedimentation rate. Thus in 2006 the volume of sediment accumulated is 63 000 mcm, or 23 % of the total storage capacity. This is forecasted to increase to a volume of 181 000 mcm by 2050. This will mean that only 35 % of the current total storage supply will be free of sediment.

2.2.8.3.7 North America

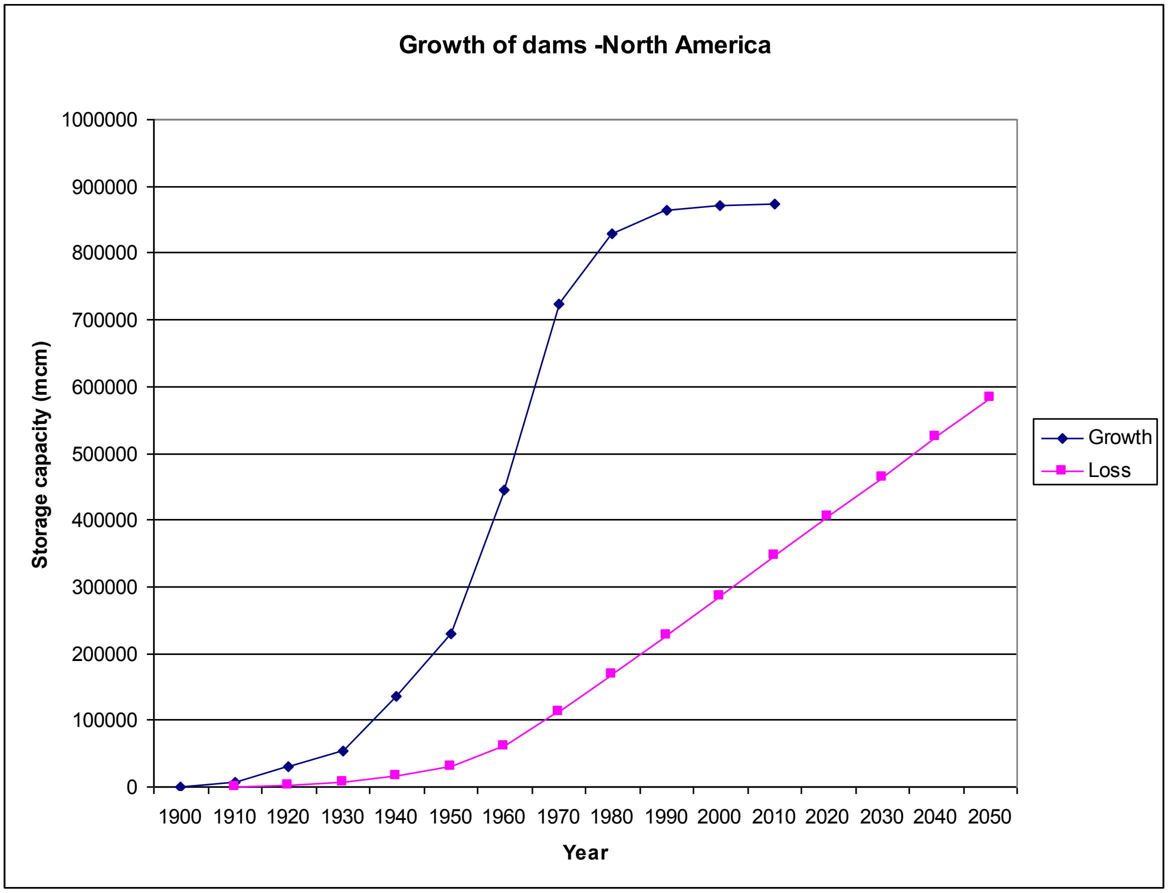


Figure 2.2-37 Growth of dams - North America

The curve for North America is based on the results found for America only. The curve was seen to show the typical shape. The total storage capacity for America is 872 482 mcm in 2006, with a value 66 % of the current total storage capacity being free of sediment.

The volume of sediment that has accumulated up until 2006 is 296 000 mcm, this will increase to a value of 543 000 mcm by the year 2050. This will leave 38 % of the current total storage capacity free of sediment at 2050.

2.2.8.3.8 South America

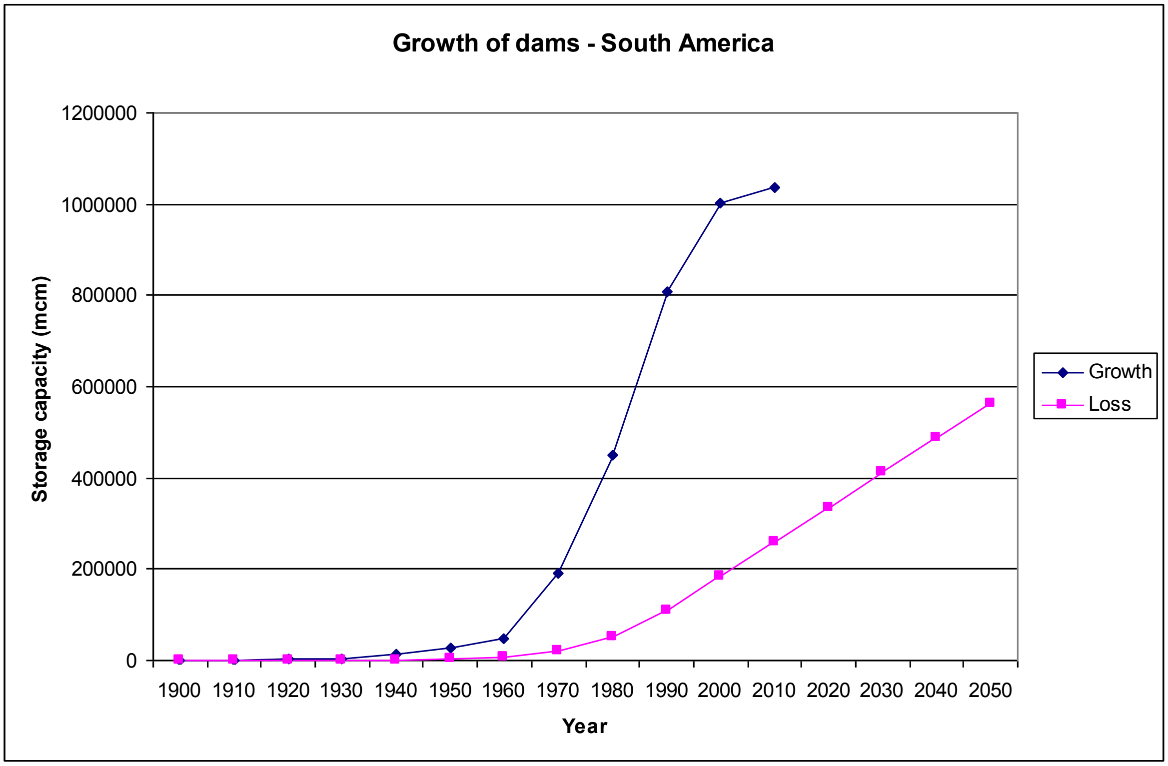


Figure 2.2-38 growth of dams - South America

Once again the curve for South America seems to show average tendencies. There is still dam construction occurring at present in South America, but at a much lower rate than was seen in the later stages of the last century. (See Figure 2.2-38 above.)

The total storage capacity for South America is 1 038 000 mcm, of this value 81 %, or 845 000 mcm, is free of sediment in 2006. The total volume of sediment accumulated by 2006 is 192 000 mcm. This value will increase to reach 522 000 mcm by the year 2050. This shows that about 50 % of the storage capacity will remain free in 2050.

As a summary to the above from Figure 2.2-31 to Figure 2.1-38, the region-wide data was summed together to produce the Global storage capacity growth curve. This has been provided below as Figure 2.2-39.

2.2.8.3.9 Global Summary

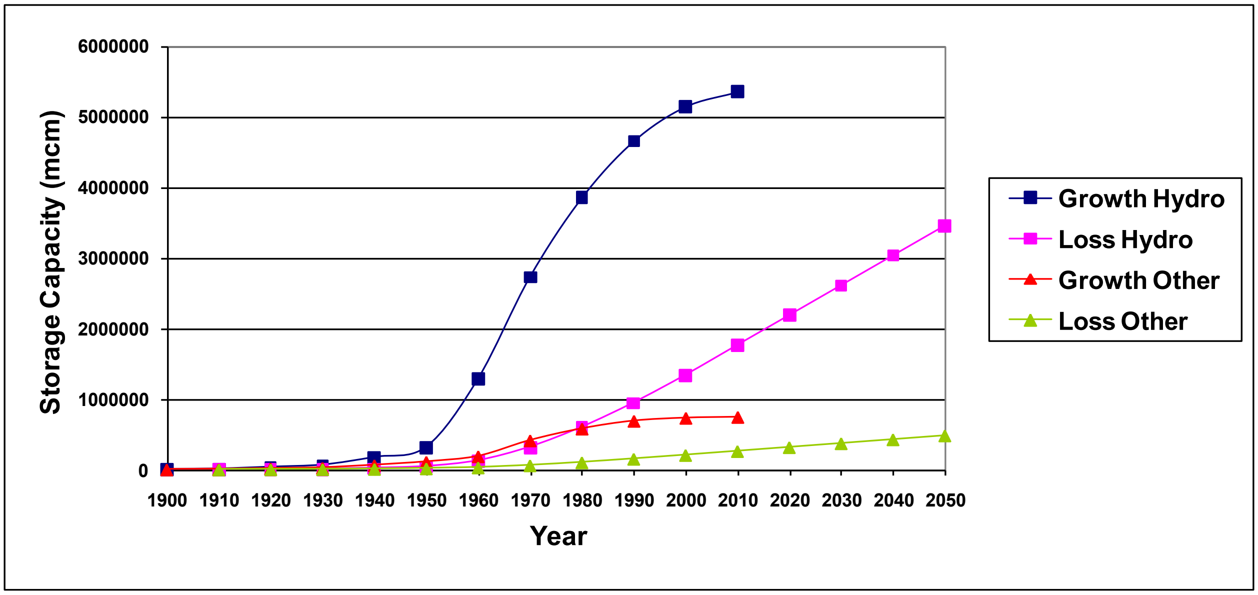


Figure 2.2-39 Global growth of storage capacity

The global growth rate of dams is similar in shape to many of the curves provided above. It shows that most of the world's storage capacity was constructed between 1950 and 1980. The rate of growth reduced abruptly after 1980, and is still slowly climbing, but the number and size of dams that are being constructed today are just a small fraction of the works that have already been completed.

The total reservoir storage capacity for the world is in the order of 6.1 x 10^{12} m^3. In 2006 the percentage of this capacity left free of sediment is 4.4 x 10^{12} m^3. That means a build up of sediment of 1.7 x 10^{12} m^3 (28 %), which, if left unchecked could potentially increase to a volume of sediment of 3.5 x 10^{12} m^3 by the year 2050. That means that by 2050 roughly 42 % of the world's current reservoir storage capacity could have been filled with sediment.

Figure 2.2-40 below shows the reservoir capacity growth over time for the various regions to illustrate the proportions contributed to the global storage capacity.

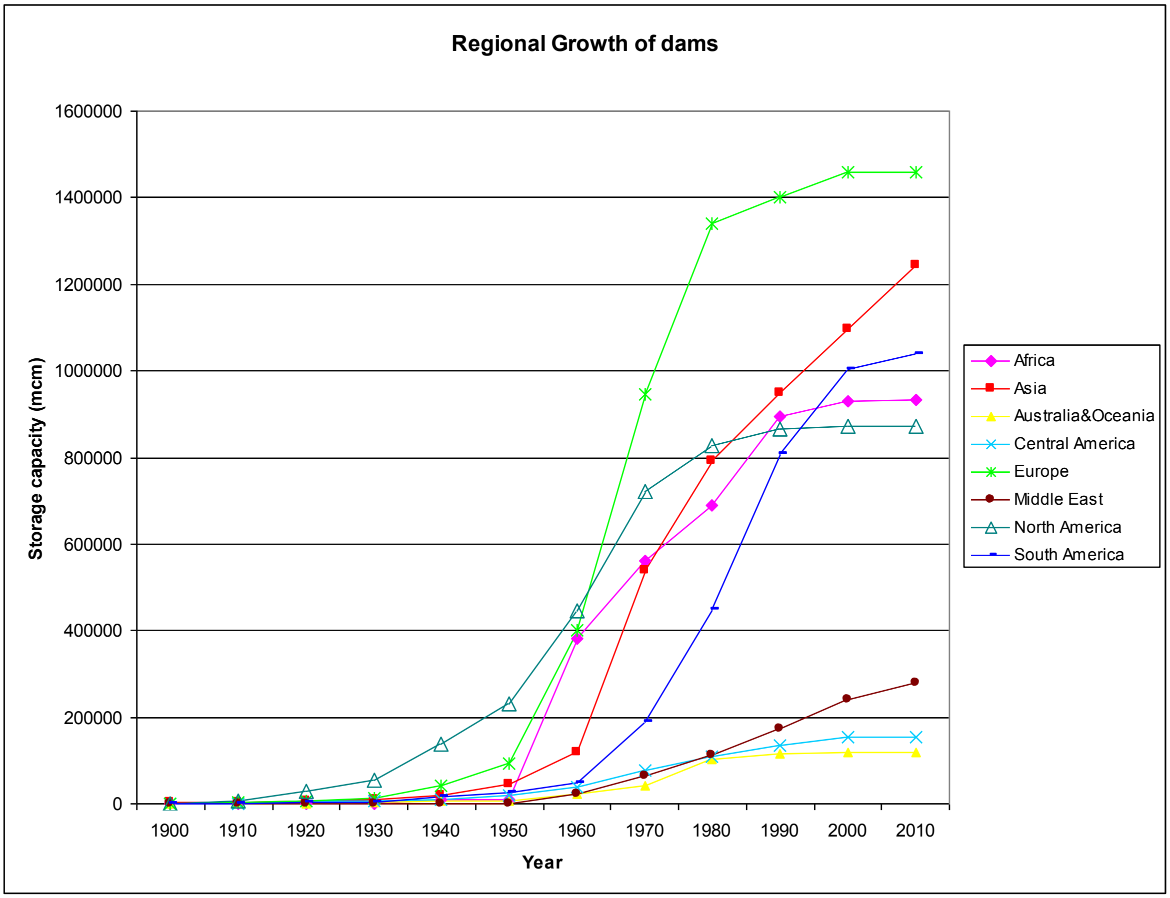


Figure 2.2-40 Components of global reservoir capacity

In an attempt to better illustrate potential problem countries, the storage capacity in 2006 was plotted alongside the storage capacity in 2050 to show how much of a reduction will occur during that period. This was done per region as shown below:

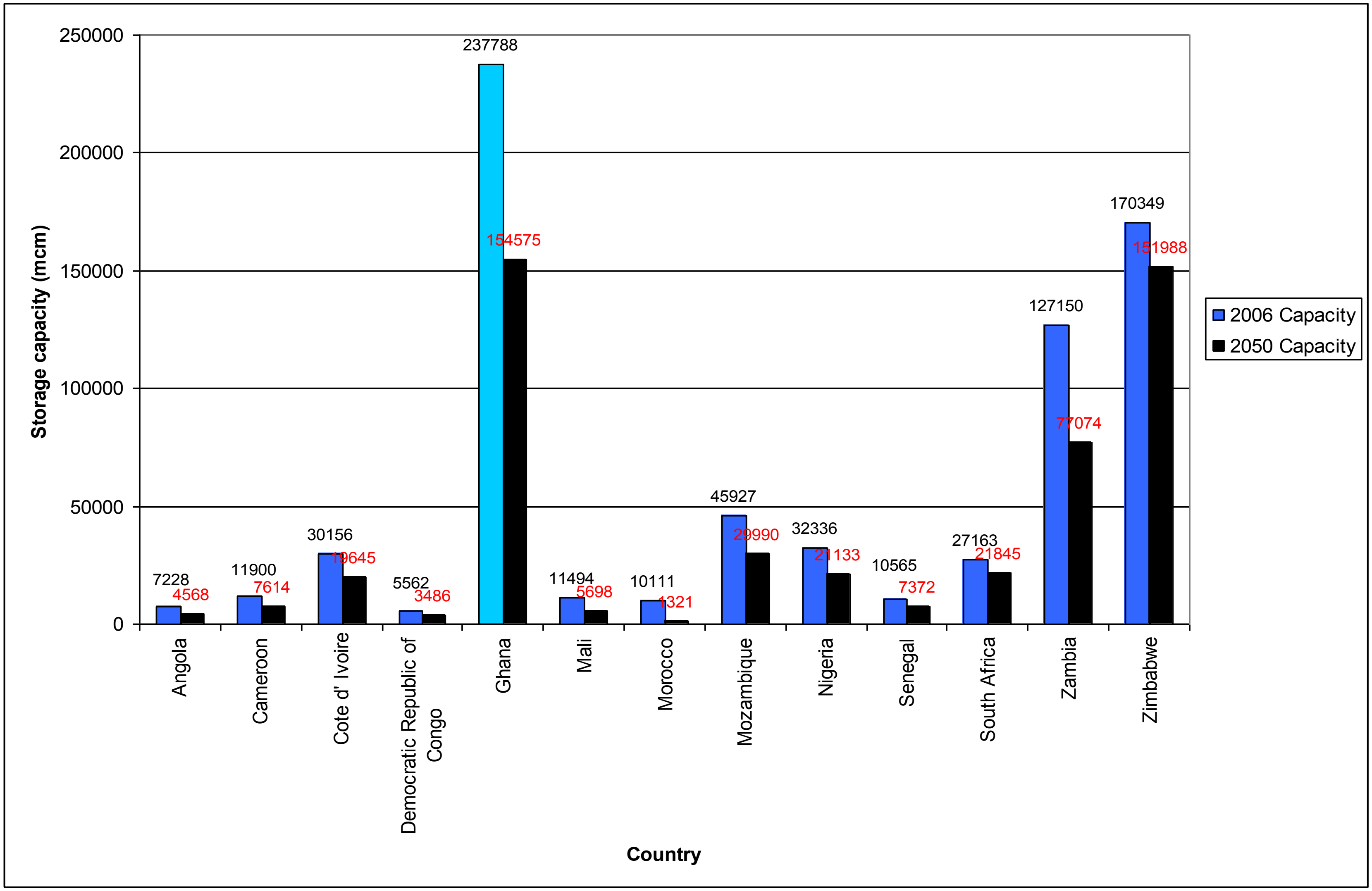


Figure 2.2-41 Current and future storage capacity (Africa 1)

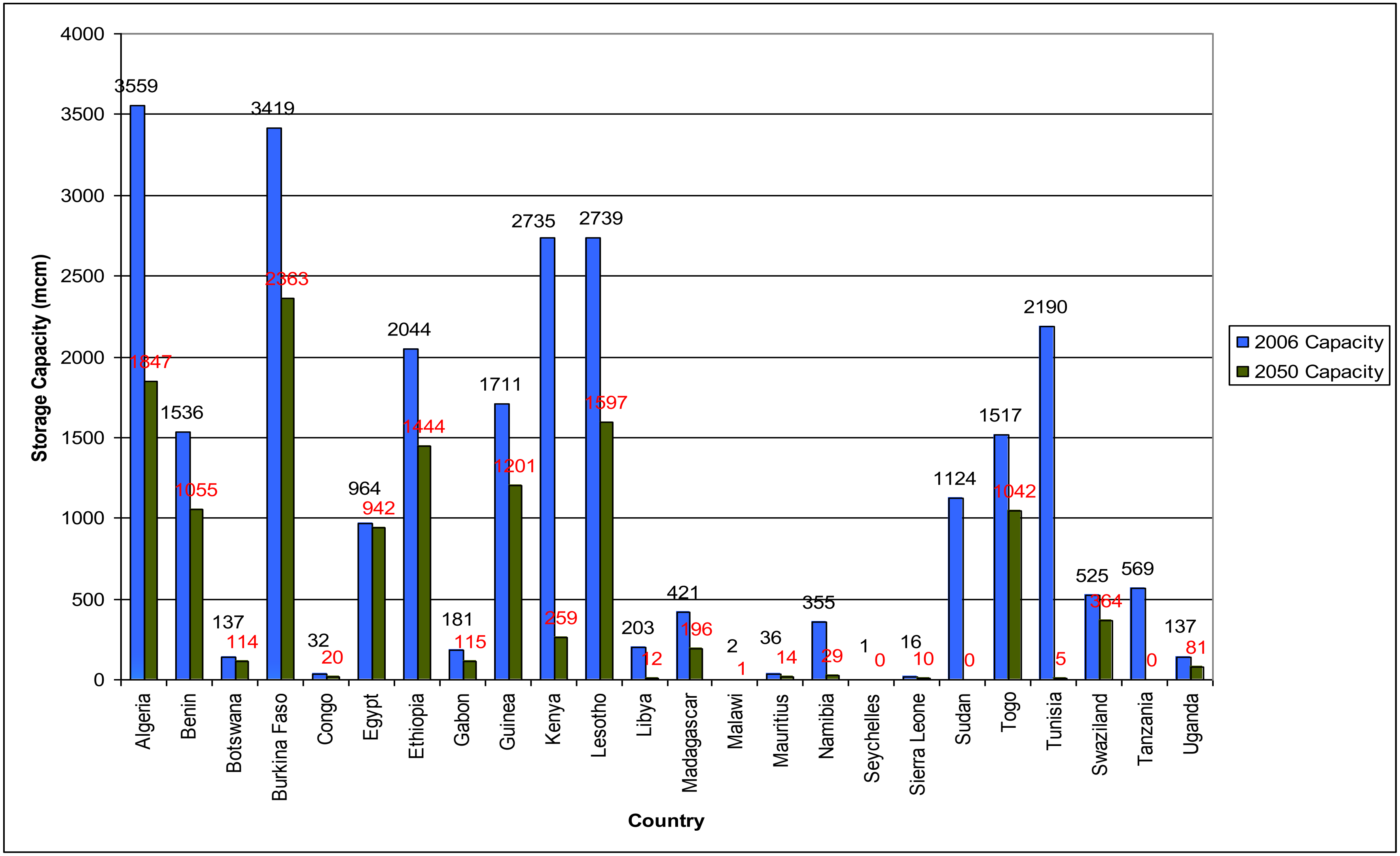


Figure 2.2-42 Current and future storage capacity (Africa 2)

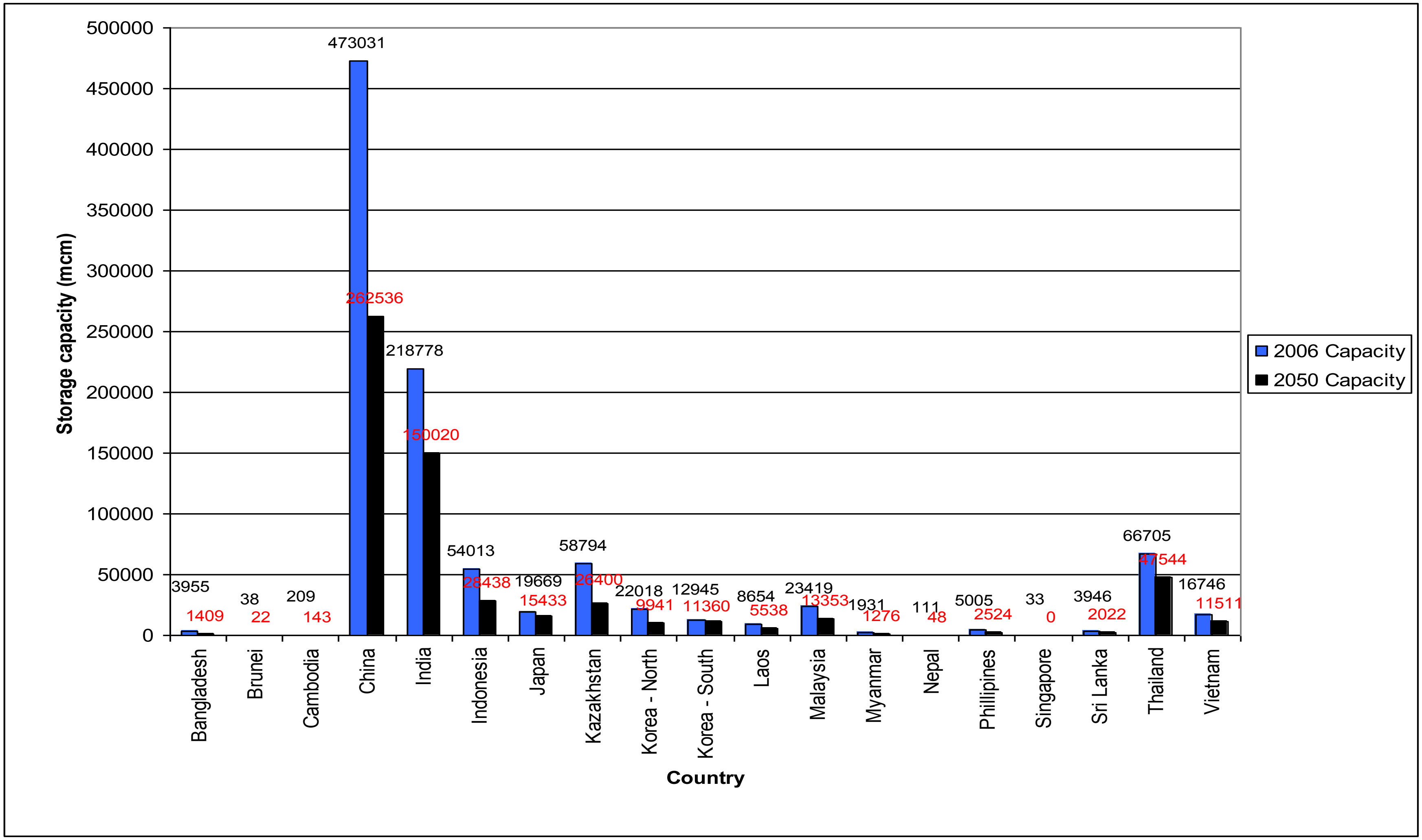


Figure 2.2-43 Current and future storage capacity (Asia)

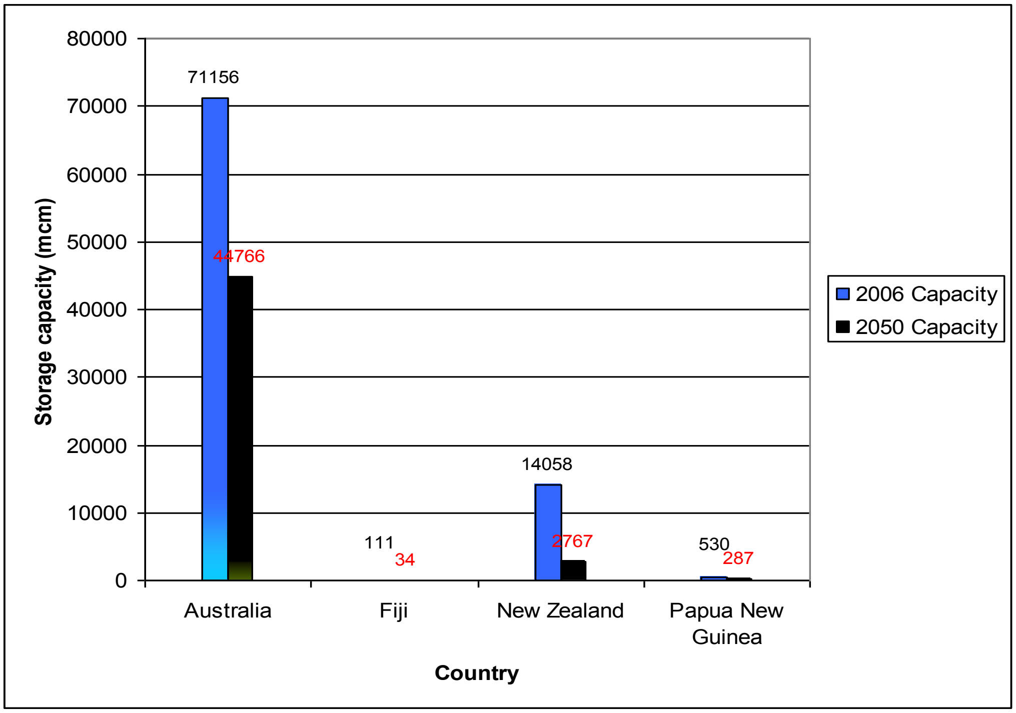


Figure 2.2-44 Current and future storage capacity (Australia & Oceania)

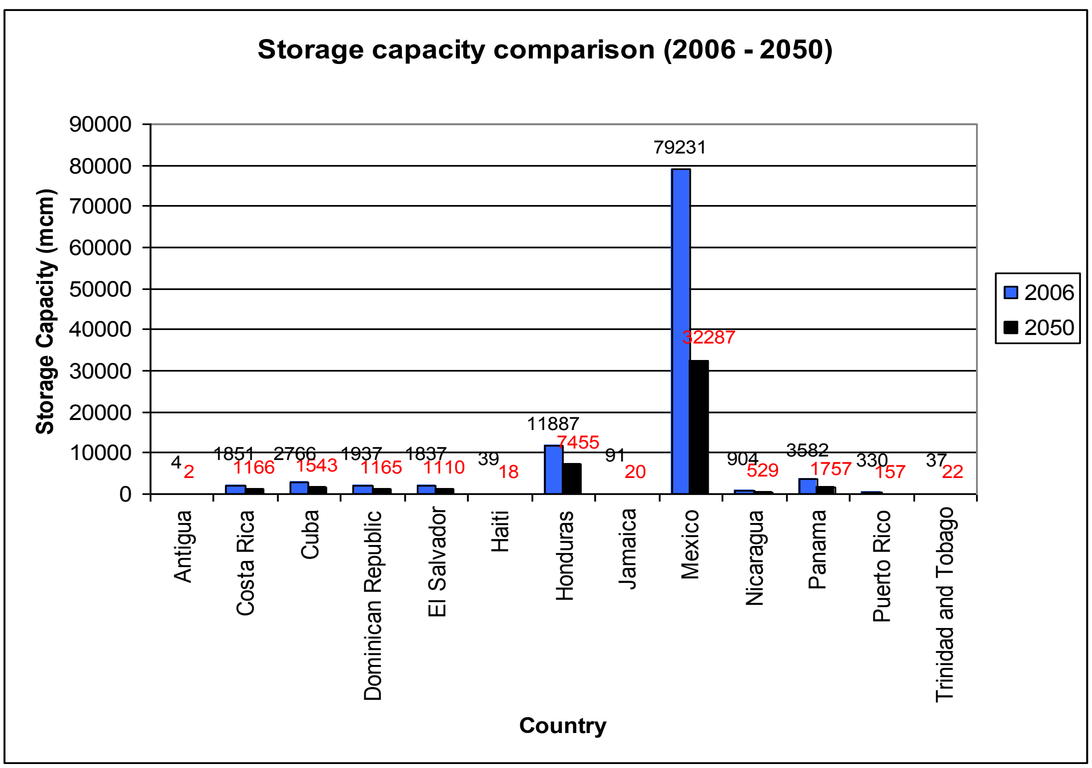


Figure 2.2-45 Current and future storage capacity (Central America)

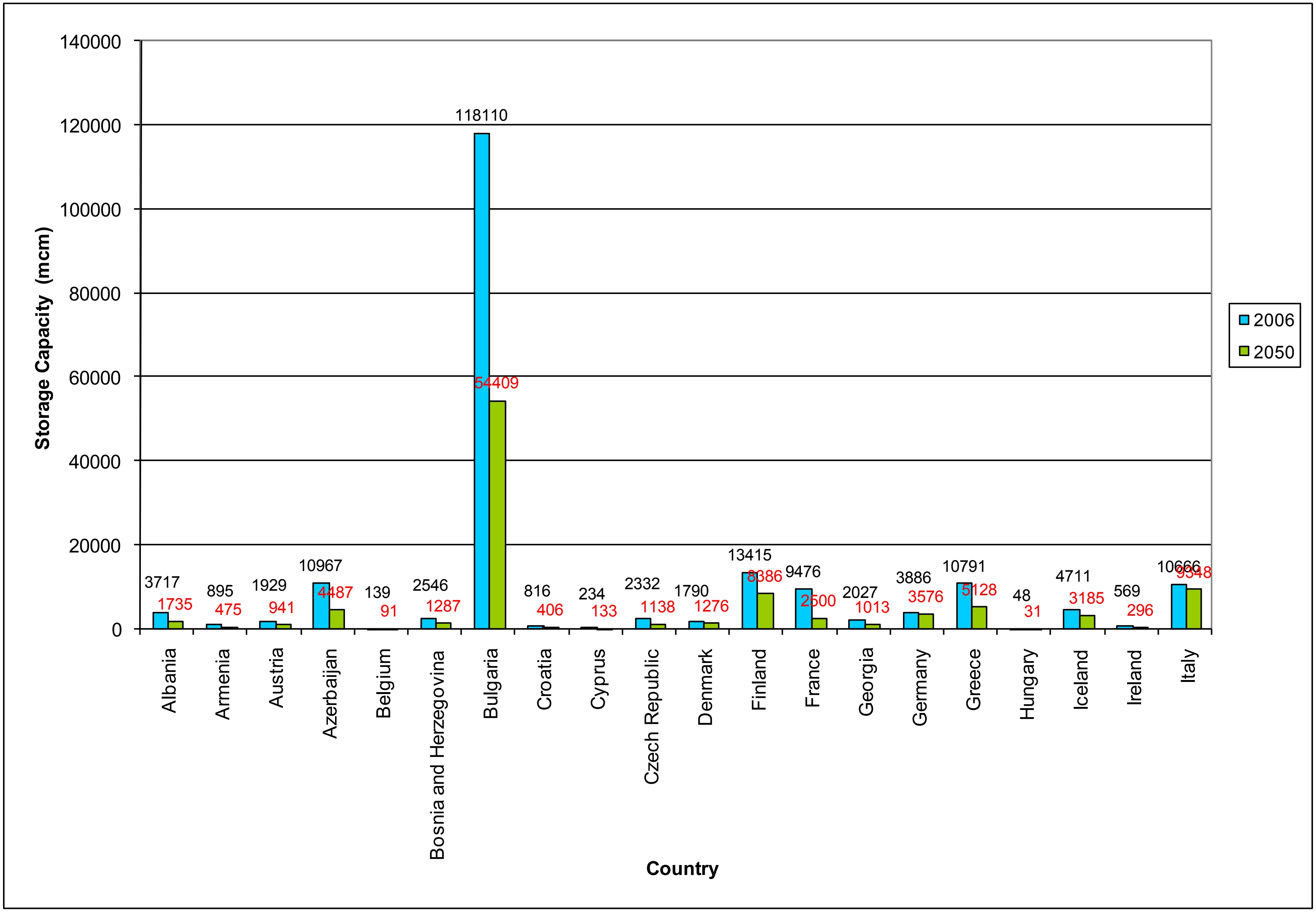


Figure 2.2-46 Current and future storage capacity (Europe 1)

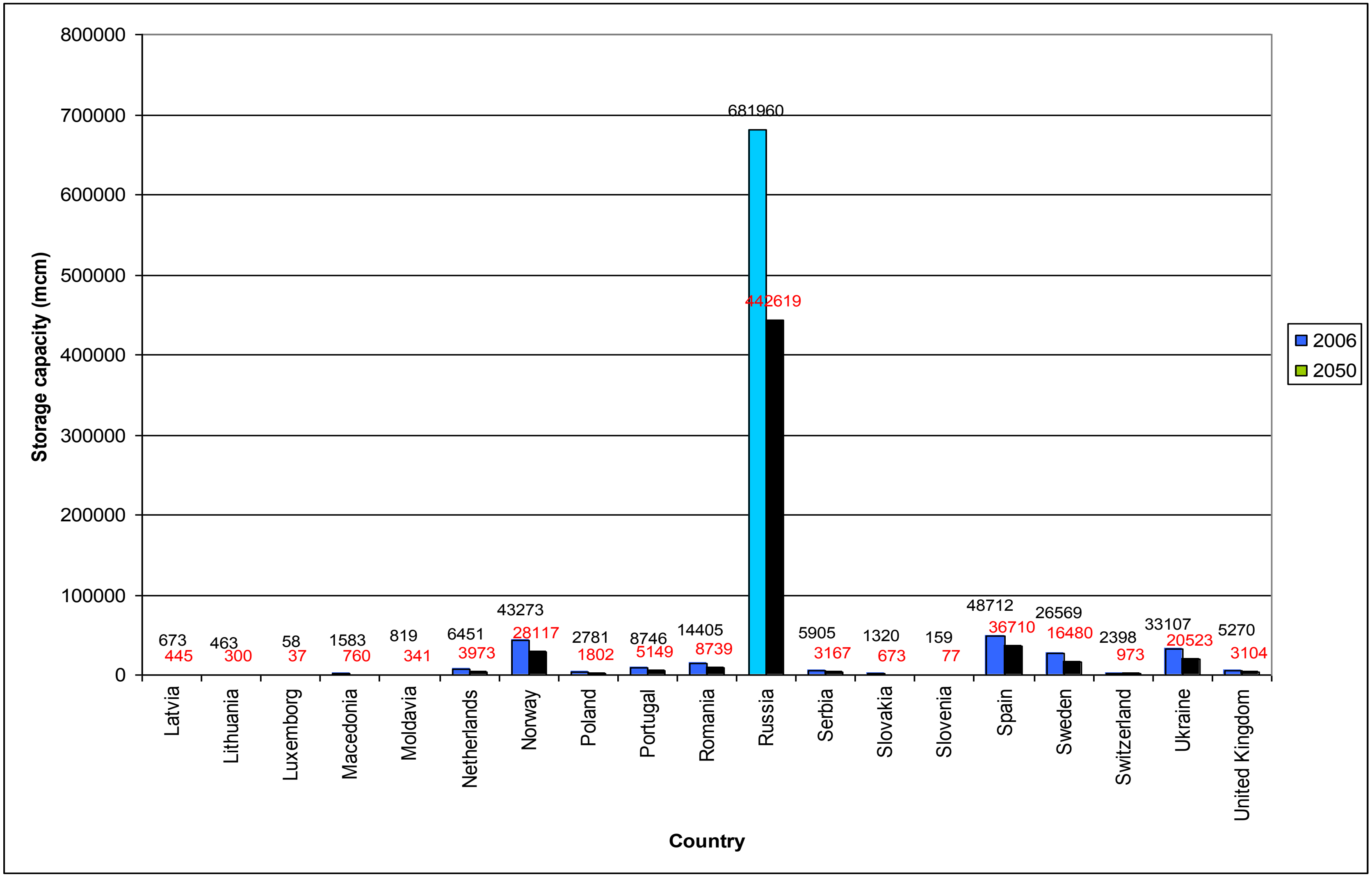


Figure 2.2-47 Current and future storage capacity (Europe 2)

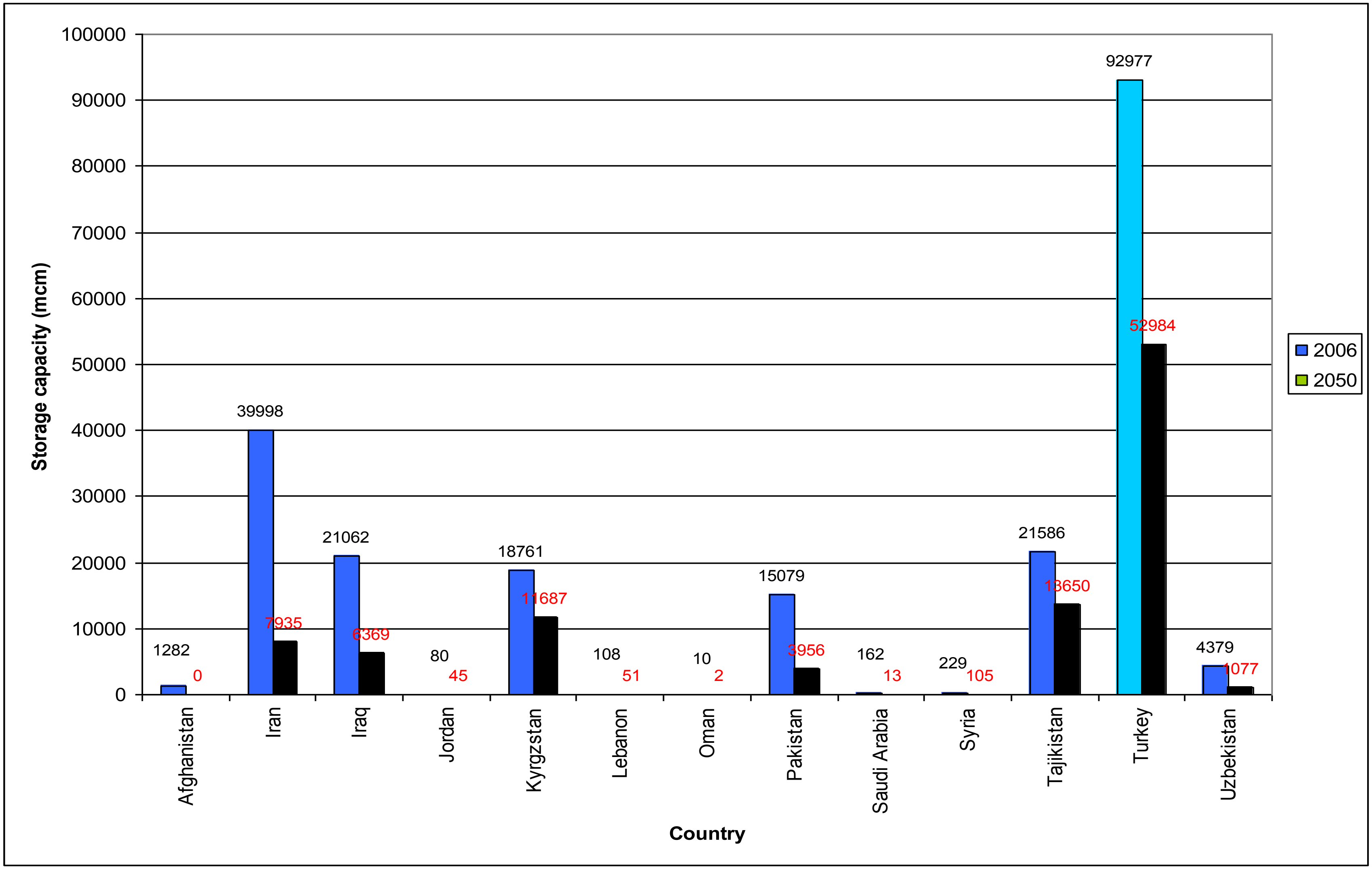


Figure 2.2-48 Current and future storage capacity (Middle East)

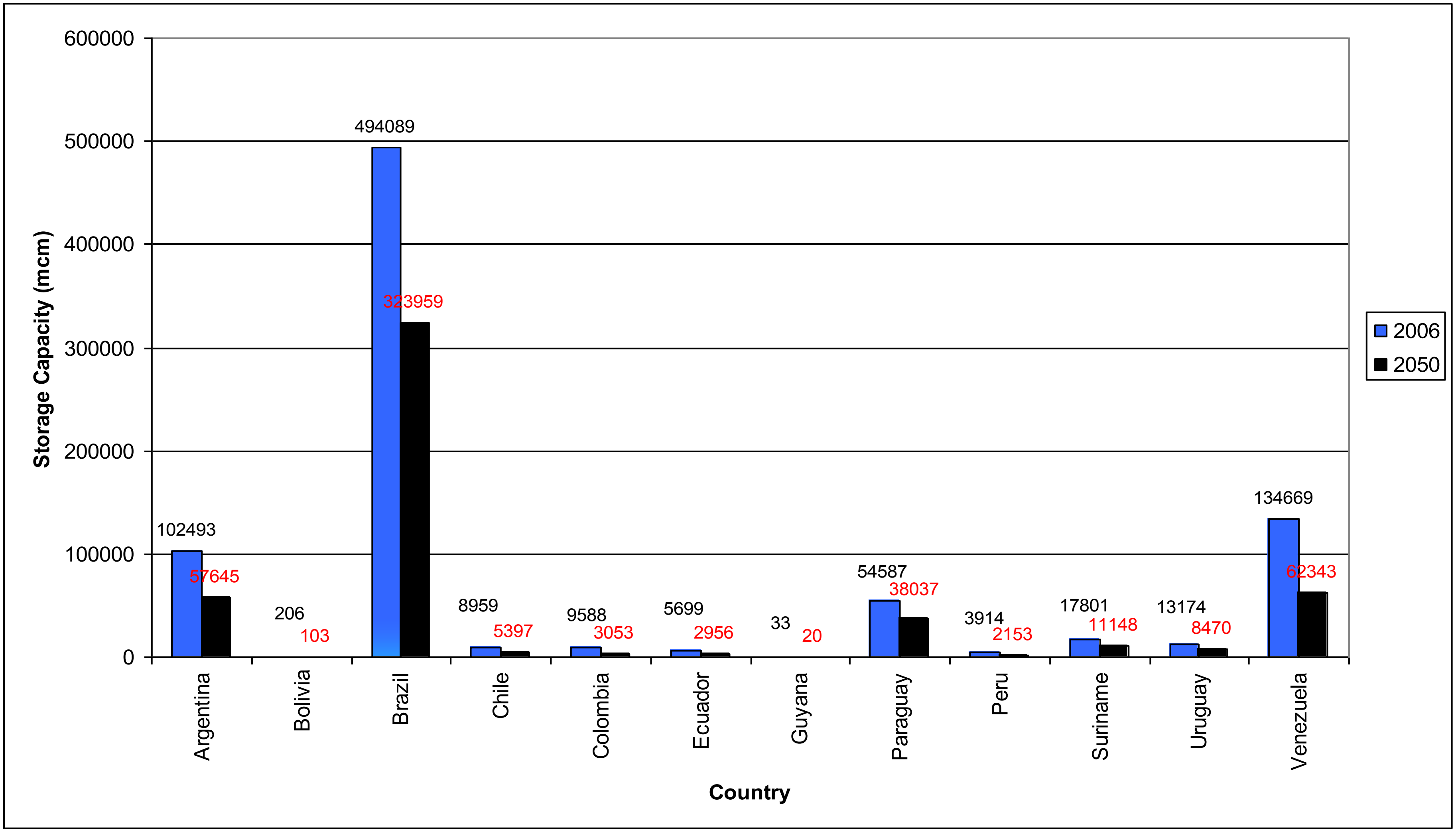


Figure 2.2-49 Current and future storage capacity (South America)

The regions of Europe and Africa were split onto two separate graphs in the preceding section. This was done to increase the readability of them. The graph for North America was omitted, as the only country on it was USA. For the USA in 2006 the available storage capacity is 576 171 mcm and this will decrease to a value of 329 243 mcm by the year 2050.

2.2.8.4 Potential impacts on storage capacity for different reservoir purposes

The article mentioned previously in this report (Lempérière, 2006) also states the following:

"The impact of sedimentation is by no means the same for hydropower as for other dam functions. For hydropower, corresponding to more than 80 per cent of the total storage, part of the sedimentation is in the dead storage, with little or no impact, and part affects the live storage, where a reduction of 50 percent means a much lower reduction in power production. A reduction of storage of 0.3 percent per year means a reduction of power of much less than 0.1 percent of production, that is, less than 10 percent in a century."

Using the method explained in this report it was seen, that globally, there was an average sedimentation rate of 0.8 %/ year and a weighted average sedimentation rate of 0.7 %/ year. After summing the regional growth rate curves to arrive at the global growth rate curve, it was found that hydropower dams made up 81.5 % of the worlds total current storage capacity. So the excerpt from the above article was accurate when it said that 80 % of the total storage was for hydropower. It was also seen that in 2006, 35 % of the total storage capacity for hydropower had been filled with sediment. In 2050 this proportion of current total capacity that would have been filled with sediment has risen to 70 %. (See Figure 2.2-50 below)

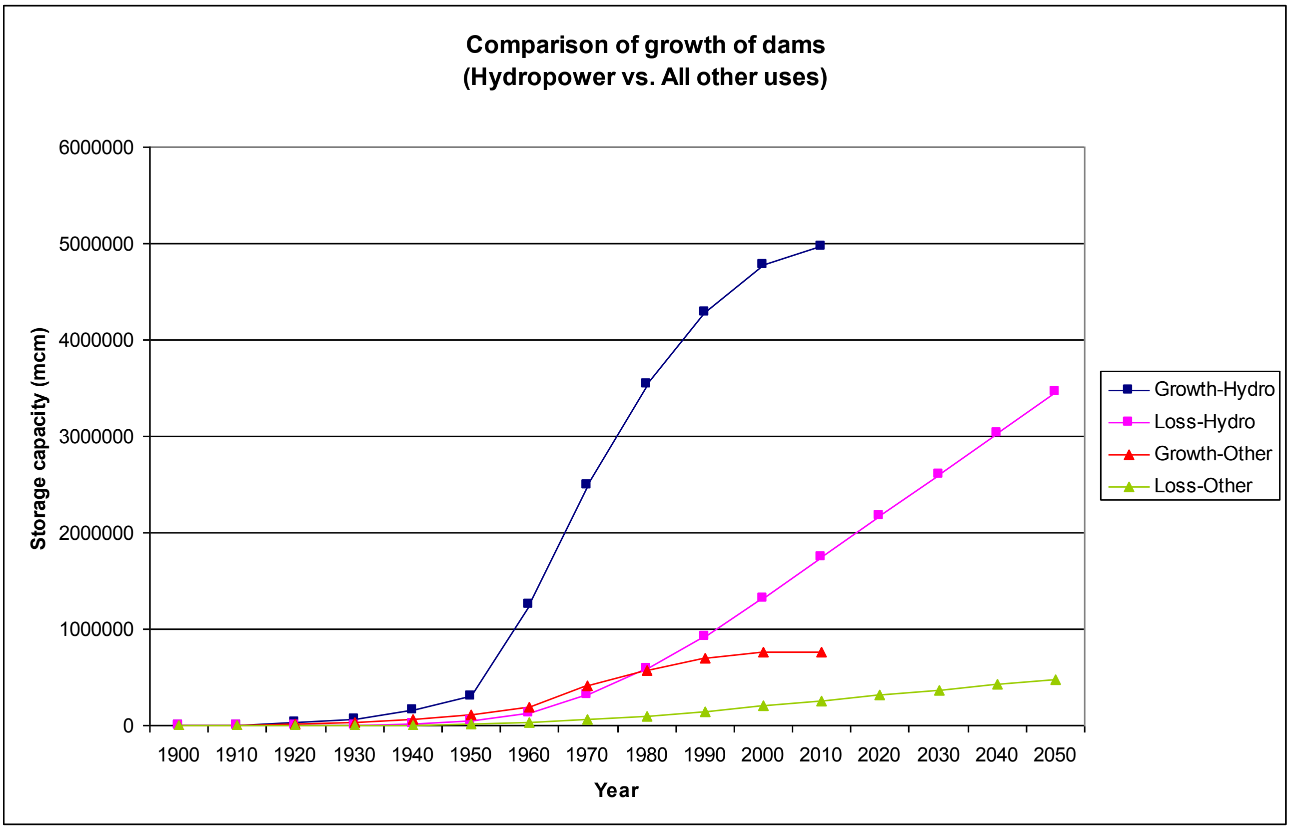


Figure 2.2-50 Global comparison of growth of dams by purpose

For dams for any other purpose, in 2006, 33 % of the available capacity was filled with sediment, rising to a value of 62 % by 2050. So it is not as high as that for hydropower dams.

To quantify the actual impacts on the yield from these dams, the following was done:

2.2.8.4.1 Dams for all other purposes

It is expected that non-hydropower dams will be severely impacted on when they reach a 70 % sedimentation level. At this sedimentation level there will be about a 40 % to 50 % water yield reduction, and there will begin to be problems at the intakes. Based on the Global data this could occur by the year 2065, and will occur per region as indicated below in Table 2.2-14:

Table 2.2-14: Current non-hydropower 70 % depletion date

Region	Non-hydropower dams: Date 70 % filled with sediment
Africa	2090
Asia	2025
Australasia	2080
Central America	2040
Europe and Russia	2060
Middle East	2030
North America	2070
South America	2060

2.2.8.4.2 Hydropower dams

Hydropower dams can generally be filled to a higher level than non-hydropower dams, as it is mainly necessary to maintain the head for the power generation, and a storage capacity sufficient to meet all expected demands for power. It is expected that hydropower dams will be severely impacted when they reach a level of sedimentation of 80 %. Based on the global data this could occur by the year 2070, and per region as indicated in Table 2.2-15:

Table 2.2-15: Current hydropower 80 % depletion date

Region	Hydropower dams: Date 80 % filled with sediment
Africa	2100
Asia	2035
Australasia	2070
Central America	2060
Europe and Russia	2080
Middle East	2060
North America	2060
South America	2080

2.2.9 Summary

It is interesting to see that the number of large dams (>15m) that have been constructed worldwide occurred at a rate of 1.2 dams/ day since 1930. This figure is based on the number of large dams registered on the ICOLD World Register of Dams. Based on the findings of this report, the following conclusion can be drawn:

The article from the International Journal of Hydropower and Dams (Lempérière, 2006), mentioned previously in this report, states that a sedimentation rate of 0.3 %/ year was what should be expected on a global scale. The findings in this bulletin show that the sedimentation rate was:

For countries with recorded data	=	0.96 %/ year;
Predicted average sedimentation rate	=	0.8 %/ year;
Predicted weighted average sedimentation rate	=	0.7 %/ year;

The first value is simply the average sedimentation rate for the countries that data was collected from. The second value is comprised of the countries with recorded data incorporated with the predicted values, for the remainder of the countries, and is just a numerical average. Finally, the third value is average of the predicted and recorded data weighted by the storage capacity of each country.

The current total large dam reservoir storage capacity for the world is 6100 km^3. In 2006 the storage capacity left free of sediment was 4100 km^3 which means a build up of sediment of 2000 km^3 (33 %), which, if left unchecked could potentially increase to a volume of sediment of 3900 km^3 by the year 2050 (based on current storage capacity). This means that by 2050 roughly 64 % of the world's current reservoir storage capacity could be filled with sediment.

Hydropower dams make up 81.5 % of the world's total current storage capacity and are typically only affected by sediment when more than 80 % of the total storage capacity is lost, while for non-hydropower dams the yield is seriously affected when 70 % of the total storage is lost.

Countries that could experience critical sedimentation volumes by year 2050 are: Afghanistan, Albania, Algeria, Bolivia, Botswana, China, Columbia, Ecuador, France, Fiji, Iran, Iraq, Jamaica, Kenya, Libya, Malaysia, F.Y.R.O. Macedonia, Morocco, Mexico, Namibia, New Zealand, Oman, Pakistan, Puerto Rico, Saudi Arabia, Singapore, Sri Lanka, Sudan, Tanzania, Tunisia and Uzbekistan. Almost one third of these countries are in Africa. Figure 2.2-51 shows the regions where the economies are directly affected by drought, and many of these critical sedimentation (by 2050) countries are in the high drought vulnerability zones.

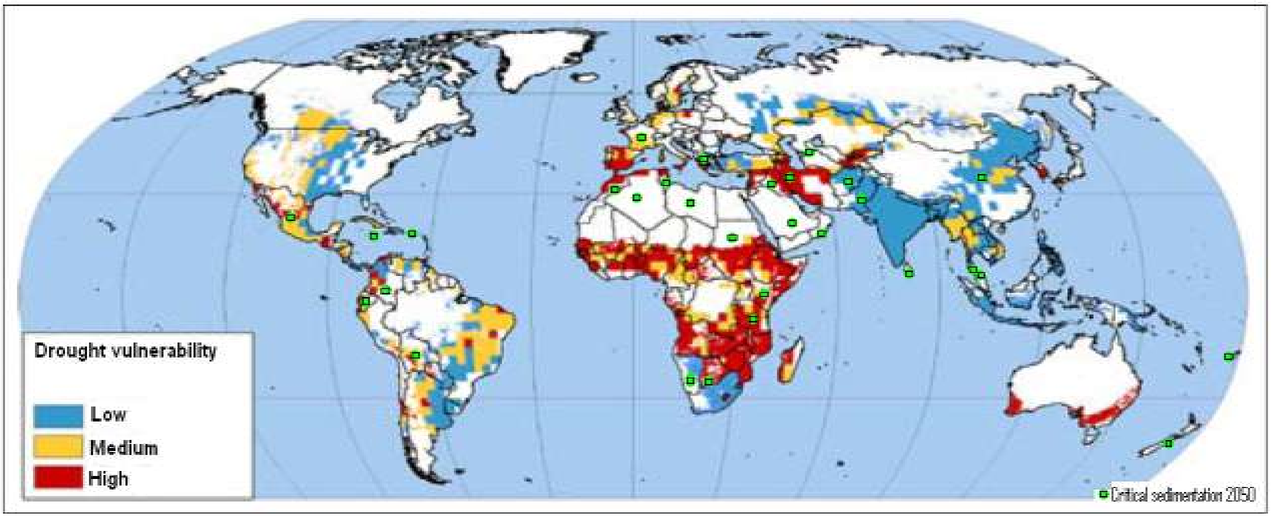


Figure 2.2-51: Drought proportional economic loss (UNDP)

2.3 Upstream impacts

Damming created by a dam results in reduced sediment transport capacity upstream of the dam and sediment deposition. Sediment deposition results in the loss of live storage capacity. In many cases sediment deposition also occurs above the full supply level of the reservoir, sometimes constituting more than 10 % of the deposited sediment. As sediment deposition continues, the sediment delta grows higher and eventually flood levels start to rise. Not only flood levels are affected, but also drainage from agricultural land, bridge discharge capacity, pump station and hydropower operation and navigation. In the semi-arid climate such as in parts of Africa, the primary effect of reservoir sedimentation is however the loss in storage capacity for domestic or industrial supply and irrigation.

3. Downstream fluvial morphological impacts of a dam and possible mitigating measures

3.1 Background

Kariba Reservoir on the Zambezi River, Zimbabwe/Zambia, has a surface area of about 5500 km^2 at full supply level and a full supply capacity of over 180 km^3. Gariep Reservoir on the Orange River, South Africa, has an original full supply capacity of 5950 million m^3. Considering the large sizes of these and most of the other dams built during the past 100 years, it is not surprising that they have major impacts on the rivers downstream. However, it is not only large reservoirs that bring about changes in the rivers, but even small structures can disturb an otherwise stable river. A river compensates for the imposed changes due to a dam by adjusting to a new quasi-stable form. The closure of a dam has an immediate impact on the downstream river channel by changing the natural water discharge and sediment load. The magnitude of this impact depends on various factors:

- Storage capacity of the impoundment in relation to mean annual runoff (MAR):

  Reservoirs with large storage capacities relative to the MAR, typically absorb most of the smaller floods, attenuate larger floods and trap most of the sediments that enter the reservoir (Chien, 1985). Tarbela Reservoir on the River Indus, Pakistan, has a relatively small storage in comparison to flood volume, and thus has little impact on floods with return periods greater than 10 years. Lake Nasser behind the High Aswan Dam on the other hand has such a large storage capacity in relation to the flood volume that even the largest floods are partially absorbed (Acreman, 2000).

- Operational procedure of the dam:

  Typically dams are built for one of the following reasons: storage, hydropower, irrigation or flood detention. Many dams are also built for multiple purposes. The impacts of each type of operation are different. While a storage reservoir may release almost no water unless its storage capacity has been exceeded, a hydropower dam may release a relatively constant high flow for certain times of the day.

- Bed materials:

  Coarser bed materials like cobbles and boulders and even gravel reduce the degradation below a dam to some degree, whereas sand bed rivers are more susceptible to degradation or erosion.

- Outlet structures:

  If a dam has the necessary outlet structures, sediment can be released from a reservoir, through sluicing incoming sediments or flushing deposited sediments. The effect of the released sediment on the river channel of course depends on the operation of the outlet works.

- Sediment load:

  A dam will have a much greater impact on a river with a high natural sediment load than on a river with a low natural sediment load, because the former will experience a much greater reduction in sediment load than the latter. Also the sediments supplied by tributaries downstream of a dam can have a major effect on a river in that the flow can become oversaturated if the sediment transport capacity of the river is reduced.

There was a dramatic increase in the number and size of the dams being built after the Second World War, peaking during the 1970's worldwide. This increase in both size and capacity of reservoirs has made the impacts of dams even more obvious. Numerous studies (e.g. Williams and Wolman (1984), Chien (1985), and Hadley and Emmett (1998)) have been carried out that describe both the impacts and their causes. The primary impacts are the attenuation of flood peaks and the trapping of sediments in reservoirs, leading to changes in channel cross-section, bed particle size, channel pattern and roughness.

3.2 Changes in Discharge

The magnitude and duration of the flows released vary from one dam to another, because of the different purposes for which dams are built. Due to the relatively large storage capacities of most reservoirs, floods are either absorbed or at least attenuated and only very large floods move through a reservoir relatively unchanged. The result is a decrease in the natural variability of streamflow, as is the case below Gariep Dam on the Orange River, South Africa (WCD, 2000b). Figures 3.2-1 and 3.2-2 give an indication of what the possible impact of the proposed Jana Dam on the Thukela River, South Africa, could be on the streamflow at the dam, once the reservoir is fully utilised, without any environmental flood releases.

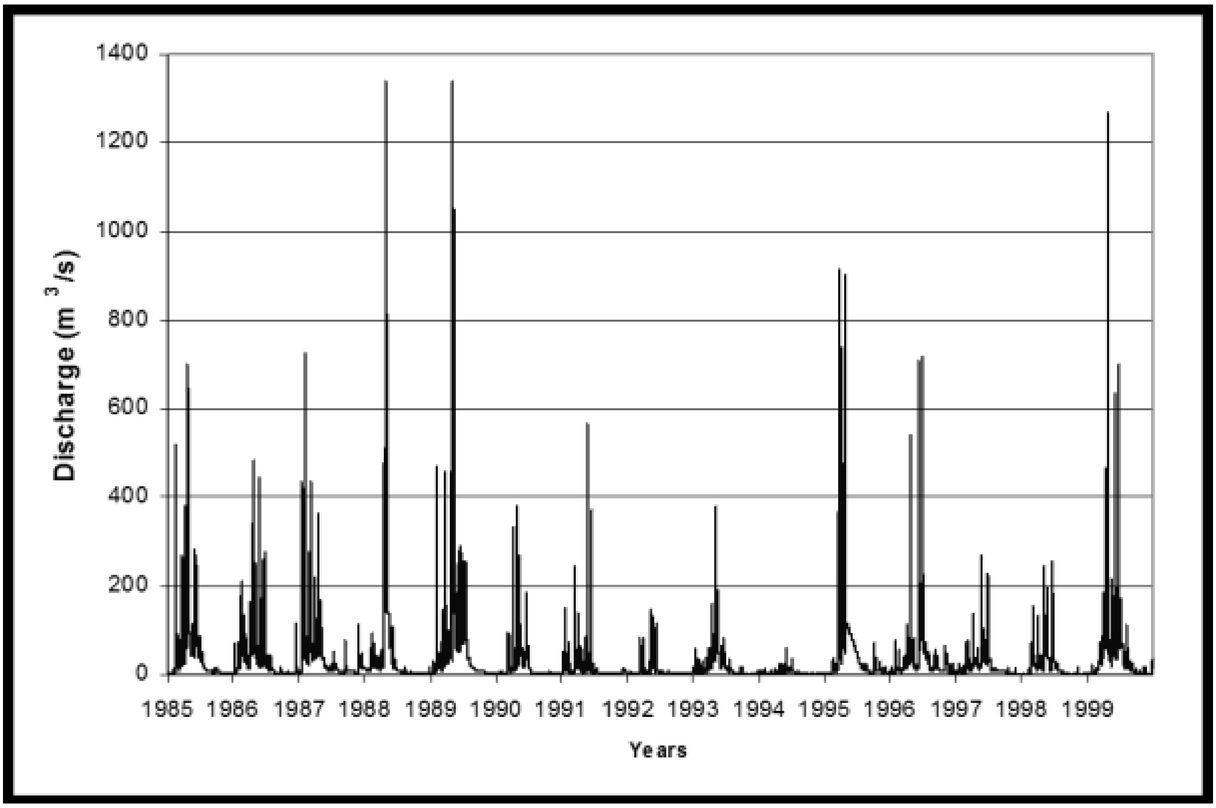


Figure 3.2-1 Pre-dam streamflow (hourly data) at proposed Jana Dam site, Thukela River, South Africa

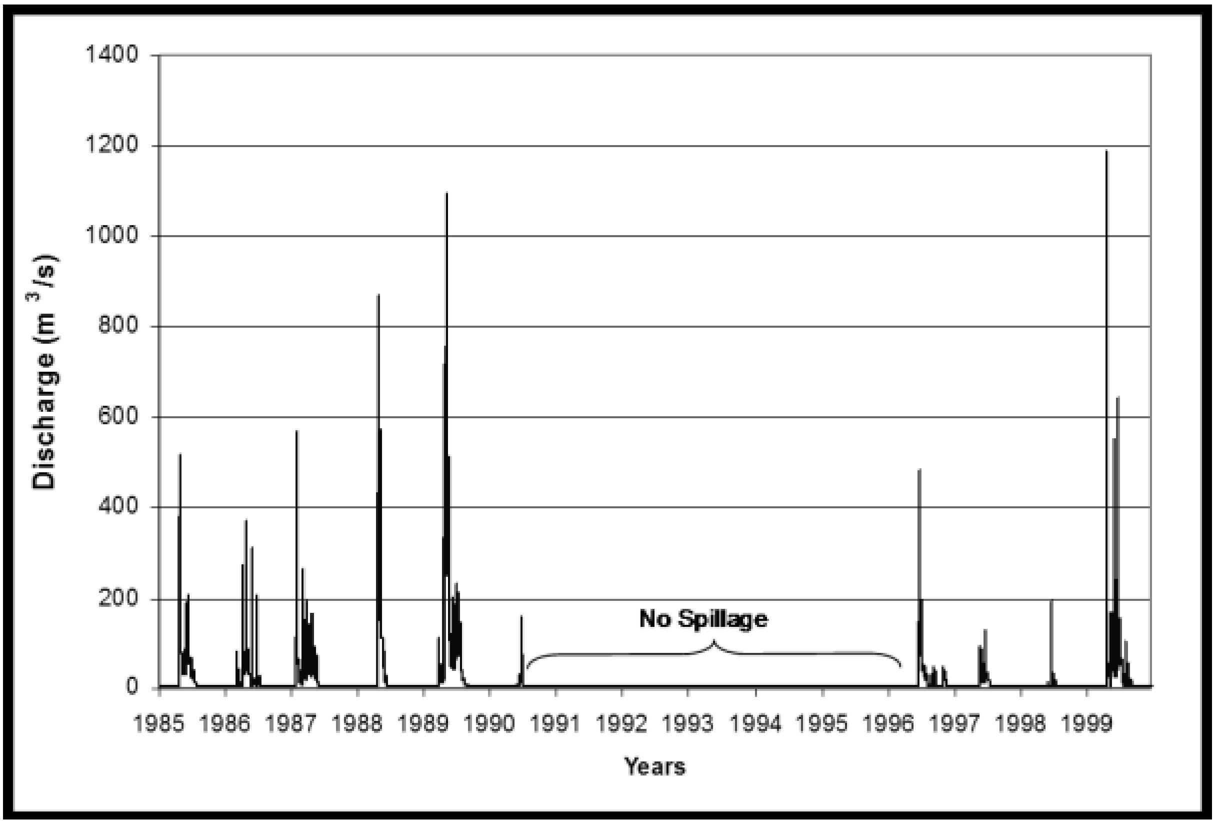


Figure 3.2-2 Post-dam streamflow (hourly data) at proposed Jana Dam site, Thukela River, South Africa

Generally the low flow duration increases and the magnitude of the flood peaks decreases. Gunnison Gorge on the Gunnison River, USA, is downstream of four reservoirs and an interbasin transfer. The 1:10-year flood peak has decreased by 53% from 422 m^3/s to 198 m^3/s while the low flow duration increased threefold according to Hadley and Emmett (1998). Andrews (1986) reported that no flows larger than 5000 ft^3/s (about 142 m^3/s) have been released from Flaming Gorge Reservoir on the Green River, USA, while the mean annual flow has not changed.

In flood detention reservoirs the low and medium flows are usually allowed to pass through the reservoir with no or limited damming, but the larger floods are greatly attenuated. According to Chien (1985), Guanting Reservoir on the Yellow River, China, has reduced the peaks by 78% from 3700 m^3/s to 800 m^3/s. Sanmenxia Reservoir, also on the Yellow River, has been operated for flood detention, with sediment sluicing, and storage since 1974, after being used solely for storage from the time it was built in 1960 to 1964. The flood peaks have been reduced from 12400 m^3/s to 4870 m^3/s, while the duration of the mean daily flows (1000 – 3000 m^3/s) has increased from 130 days a year to 204 days a year.

Reservoirs operated for irrigation decrease flows during the wet season to store water, and increase flows during the dry season, thereby maintaining relatively constant low flows, usually higher than pre-dam conditions. Hydropower dams on the other hand possess highly variable release patterns, with relatively large flows being released during certain times of the day and no or low flows during the rest, although Kariba Reservoir on the Zambezi River, Zimbabwe/Zambia, manages to release a minimum flow of 283 m^3/s (SI and CESDC, 2000), which is rather the exception. The effect of hydropower generation at Glen Canyon Dam, USA, on the Colorado River streamflow can be seen in

Figure 3.2-3. Construction work officially began on Glen Canyon Dam in 1956 and turbines and generators were installed between 1963 and 1966 (Glen Canyon Dam Website, 2002).

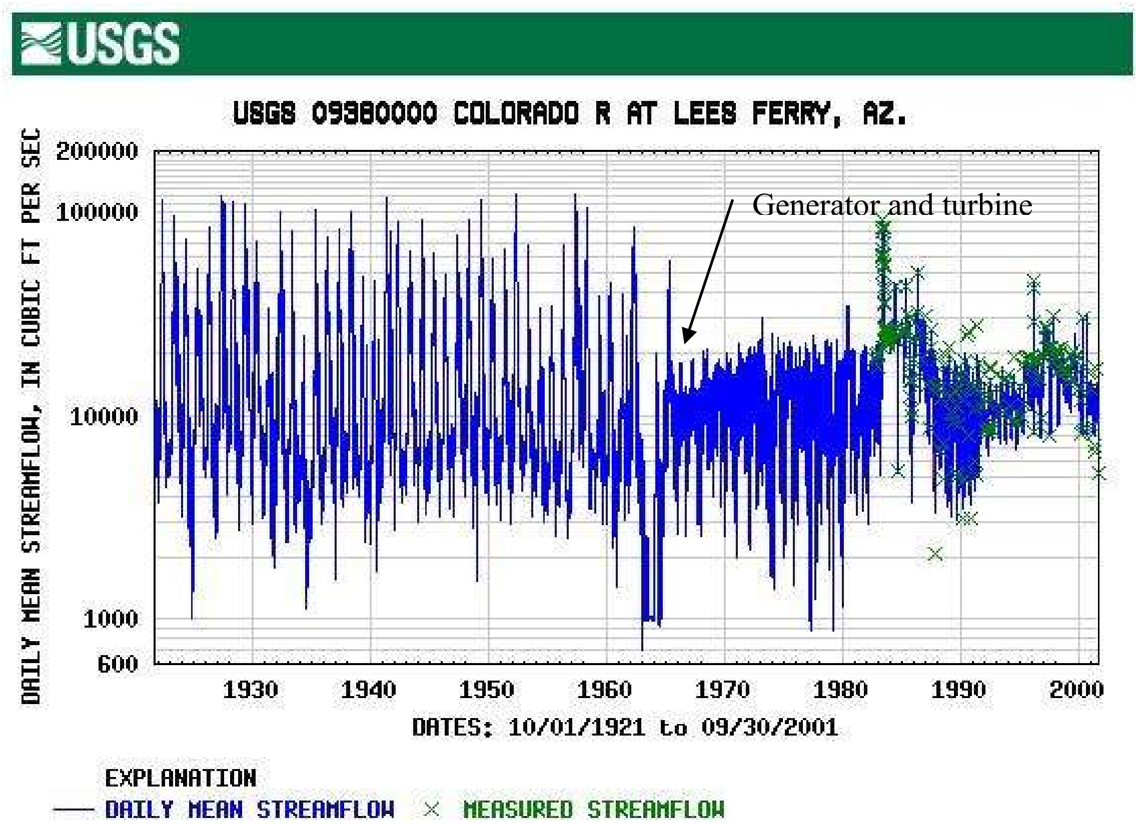


Figure 3.2-3 Colorado River streamflow downstream of Glen Canyon Dam, USA, before and after dam construction (USGS, 2002a)

3.3 Changes in Sediment Load

Together with the reduction in flood peaks a drastic decrease in the sediment volumes released from a reservoir is experienced, unless the dam is equipped to sluice or flush sediments through the reservoir. Williams and Wolman (1984) reported that the trap efficiency of large reservoirs is commonly greater than 99% in the USA.

Glen Canyon Reservoir (Figure 3.3-1) on the Colorado River has reduced the average annual suspended sediment load by 87% from 126 million tons/a to 17 million tons/a (Williams and Wolman, 1984). The downstream station at which the measurements were taken is 150 km away from the dam, which shows that the dam’s influence extends far downstream. The impact of a dam on the sediment load however decreases with distance from the dam, as can be seen downstream of Canton Dam on the North Canadian River, USA (Figure 3.3-2). The control station included in the figure indicates that the upstream sediment load has remained unchanged, whereas the downstream reach has experienced a considerable reduction in sediment load. Also below Flaming Gorge Dam on the Green River, USA, tributaries have replenished the sediment supply within 68 miles downstream according to Andrews (1986).

Figure 3.3-1 Glen Canyon Dam with Lake Powell in the background

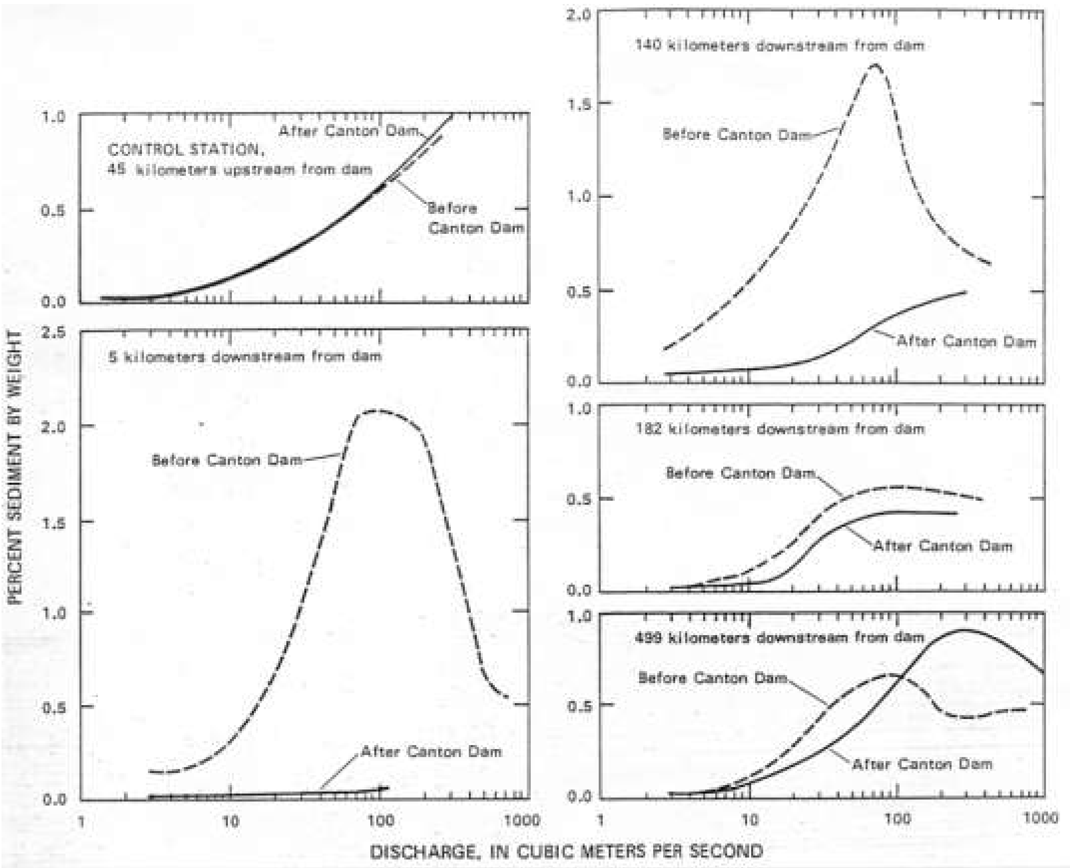


Figure 3.3-2 Suspended sediment loads at successive downstream stations before and after the closure of Canton Dam on the North Canadian River, USA (Williams and Wolman, 1984)

Not only are sediments trapped in a reservoir, but the transport capacity in the downstream channel also decreases due to the attenuated flood peaks and is diminished by coarsening of the bed and flatter bed slopes associated with bed degradation. Downstream of Danjankou Dam on the Han River, China, the sediment concentration at flows of 3000 m^3/s was reduced by 60.4% (Chien, 1985) and downstream of the High Aswan Dam on the Nile, the suspended sediment concentration typically measured during August decreased from 3500 mg/ℓ to 100 mg/ℓ (Schumm and Galay, 1994).

3.4 Changes in Channel Depth

The changes in flow regime and sediment load have a dramatic effect on the channel morphology, since these are two of the controlling factors. Due to the large amounts of clear water released from most reservoirs the most common response of the river channel downstream is degradation. After the completion of Sanmenxia Dam, the average bed degradation was between 0.6 m and 1.3 m during the first four years of storage operation (Chien, 1985). Williams and Wolman (1984) reported much greater impacts below Hoover Dam on the Colorado River, USA, where the maximum degradation 13 years after the completion of the dam was 7.5 m. In most cases the maximum degradation will occur directly below or near the dam, which is the case at the High Aswan Dam with a maximum degradation of 0.7 m (Schumm and Galay, 1994), whereas at Glen Canyon Dam a 7.25 m bed level lowering was measured 16 km downstream of the dam (Williams and Wolman, 1984). Figure 3.4-1 shows the variation in bed degradation, nine years after the completion of the dam, with distance downstream of the dam.

The amount of degradation will depend on local controls such as bedrock or the development of an armour layer. Armouring occurs when fine materials in the bed are eroded, leaving the coarser fractions behind. These create a protective layer that limits erosion of the underlying particles. Likewise flattening of the channel slope will decrease the flow competence, which will control degradation.

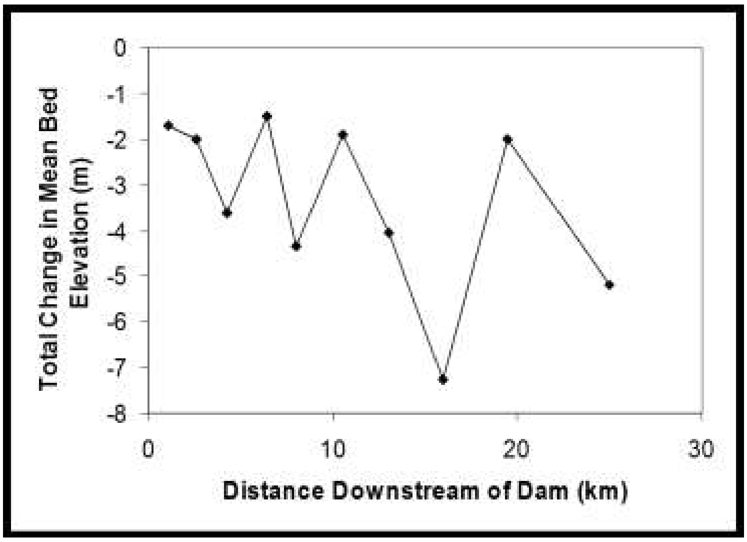


Figure 3.4-1 Variation of bed degradation (nine years after closure of the dam) downstream of Glen Canyon Dam, USA (Williams and Wolman, 1984)

The Lesotho Highlands Water Project (LHWP) tunnel transfers water from Lesotho to South Africa. En route electricity is generated in Lesotho before the water is discharged, via the Delivery Tunnel, into the Ash River, South Africa. The hydropower station was constructed only after the water transfer system had been operational for some time and once the hydropower station was operated at peak discharge (with discharges up to a maximum of 50 m^3/s (equivalent to a 1:10-year flood at the outfall) for a few hours each day), problems became apparent within a year. The variable discharge, leading to alternate wetting and drying of the riverbanks, caused substantial degradation of the riverbed (3 to 5 m) and slumping of the riverbanks, changing the river from a small stream to a deep, wide river (see Figures 3.4-2 to 3.4-5). Figure 3.4-2 shows the observed bed degradation that took place within two years, with as much as 6 m scour in places. Also indicated in the figure are the simulated and estimated bed profiles with a proposed weir that is supposed to limit the erosion. The proposed weir will cause local deposition just upstream, but further upstream the erosion will still take place, unless limited by local natural controls.

Fortunately measures were taken fairly quickly and in 2001 a flood attenuation dam was built just downstream of the tunnel outlet (Figure 3.4-6), reducing the water level fluctuations to about 300 mm and dissipating much of the excess energy. As a result the riverbanks have flattened to some degree and vegetation has had a chance to establish itself on the riverbanks (Figure 3.4-7), thereby stabilising the banks. The bed slope of the river has gradually become flatter again by utilising natural and man-made controls on the river.

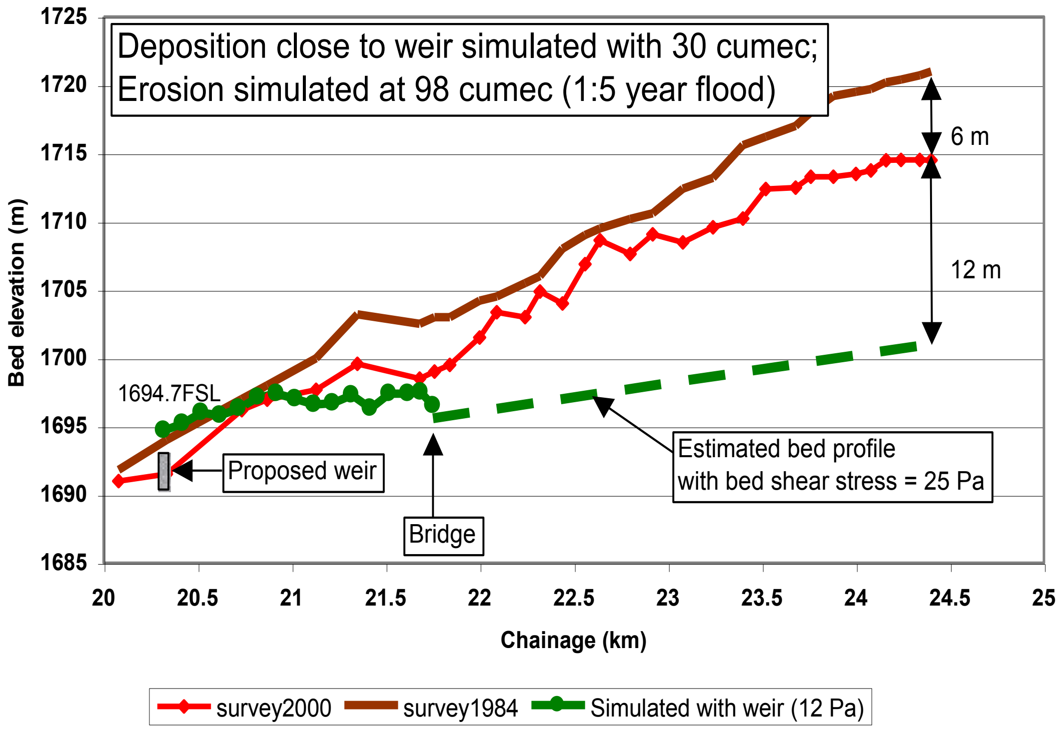


Figure 3.4-2 Ash River longitudinal profile (at site 26, with site 1 at the tunnel outfall and site 87 at Saulspoort Dam)

Figure 3.4-3 Ash River (site 20) in 1991 (HTDC, 1999)

Figure 3.4-4 Ash River (site 20) in 1997 (HDTC, 1999)

Figure 3.4-5 Ash River bed degradation (HDTC, 2000)

Figure 3.4-6 Flow attenuation dam (site 7) (HDTC, 2002)

Figure 3.4-7 Vegetation established on riverbanks (site 79) (HDTC, 2000)

Rutherford (2000) reported some scour below Keepit Dam on Dumaresq Creek, Australia, but generally scour below dams has been limited in Australia either by the exposure of bedrock or by armouring, which occurred below Glenbawn Dam, Hunter River, and Eildon Dam on the Goulburn River. Another reason for the limited amount of erosion below Australian dams is the naturally low sediment yield of the rivers, so that channels may already be adjusted to low sediment transport rates (Rutherford, 2000).

On the other hand when a certain amount of sediment is released from a reservoir the river experiences aggradation. Naodehai Dam on the Liu River, China, was built for flood detention where most of the sediment is released with the lower flows after a flood has passed. The sediment carrying capacity of the flows is exceeded by the added sediments and thus deposits in the river channel. This resulted in the bed being raised by 1.5 m over a period of 10 years (Chien, 1985). Chien also reported that the maximum aggradation occurred during the flood detention phase of Sanmenxia Reservoir.

Aggradation can also occur due to very low flows, which take place when very little water is released from a reservoir or the releases are depleted by extractions for irrigation for example. Williams and Wolman (1984) cite the Elephant Butte Dam on the Rio Grande, USA, where the decreased flows and sediment contributed by tributaries have allowed the riverbed to rise almost to the same height as the surrounding lands.

3.5 Changes in Channel Width

Unlike the changes in channel depth, which are generally dependent on the discharge, sediment load and sediment characteristics as well as local bed controls, the changes in width are also a function of the bank materials and vegetation. Cohesive banks retard erosion to some degree and an increase in vegetation adds to the stability of the banks as well as trapping of sediments. Reduced sediment loads and longer flow durations on the other hand result in widening of the channel, especially when accompanied by an increase in depth, which leads to bank undercutting and subsequent bank collapse (Williams and Wolman, 1984).

Generally a river channel widens when the channel experiences regular dry and wet periods, characteristic of hydropower dams. This could be a result of bank instability due to alternate wetting and drying of the riverbanks. Garrison Dam on the Missouri River, USA, was built for flood control and hydropower in 1953. After 23 years the maximum width increase was 625 m (from 525 m to 1150 m) 47 km downstream of the dam. In contrast a river can become narrower when it carries only low flows for long periods. During this time vegetation can encroach onto the river channel. The low flows rarely manage to reach the flood plains and even then are not competent enough to remove the established vegetation. This effectively reduces the channel width. Channel widening has been reported by Rutherford (2000) for several rivers in Australia including the Upper Murray and Swampy Plains Rivers. The channel widening is a result of consistent regulated releases that increase the duration of the near-bankfull flows.

Channel contraction usually occurs on rivers where the flows are low or are cut off completely for most of the time. Jemez Canyon on the Jemez River, USA, was built for flood and sediment control and as a result 1.6 km downstream of the dam the channel width was reduced by 250 m from 270 m to only 20 m (Williams and Wolman, 1984). Parangana Dam on the Mersey River, Australia, diverts the water and as a result the sediment delivered from the tributaries accumulates in the channel and native vegetation encroaches on the river channel. Rutherford (2000) also reported channel narrowing below several other dams in Australia, including Windamere Dam, on the Cudgegong River, and Jindabyne Dam on the Snowy River. Channel contraction can also be seen below Manapouri Lake on the Waiau River, New Zealand (Brierly and Fitchett, 2000). The Manapouri Power Scheme reduced the mean flow by 75%, resulting in a decrease in channel width from 250 m to 175 m.

The two examples from Garrison Dam and Jemez Canyon also show that the maximum change does not occur directly below a dam. In fact there seems to be no trend in the magnitude of the change in width downstream of dams.

Table 3.5-1 lists some South Africa’s rivers that have been affected by dams. Generally channel contraction has occurred.

Chelmsford Dam on the Ngagane River, South Africa, was built in 1961 and raised during the 1980’s, so that it is now a 2 MAR reservoir. Because of this large storage capacity the annual, 1:2-year and 1:5-year floods are all significantly reduced, with the 1:2-year flood decreasing from 30 m^3/s to 15 m^3/s since 1961 (based on statistical analysis). Aerial photographs from 1944 have been compared with orthophotos of the 1990’s, which show in many places that the river has narrowed over the first 10 km downstream of the dam (Figure 3.5-1).

Table 3.5-1 River width changes in South Africa

Dam	River	Pre-dam width (m)	Post-dam width (m)	% Change
Erfenis	Groot Vet	24	26	+8.3
Roodeplaat	Pienaars	26	15	-42
Bloemhof	Vaal	92	82	-11
Allemanskraal	Sand	49	21	-57
Krugersdrift	Modder	32	24	-25
Spioenkop	Tugela	53	36	-32
Albertfalls	Mgeni	32	28	-13
Theewaterskloof	Riviersonderend	37	33	-11
Glen Alpine	Mogalakwena	36	24	-33
Gamkapoort	Gamka	67	55	-18
Gariep	Orange	269	255	-5

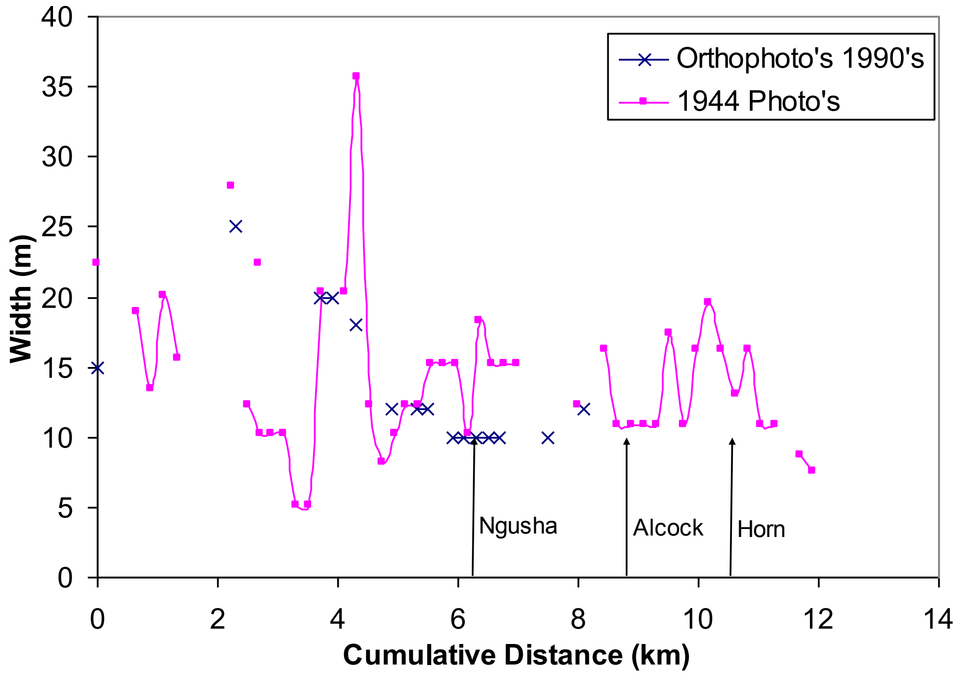


Figure 3.5-1 Ngagane River width changes downstream of Chelmsford Dam, South Africa

Pongolapoort Dam on the Pongola River was used as a case study, and the changes in width were determined from contour maps compiled before the dam was built in 1973, and 1:15 000 aerial photographs from 1996. Of the 158 cross-sections analysed, 90% have narrowed and only 10% have widened. Figure 3.5-2 shows the difference in the widths. On average the Pongola River has narrowed by 35% over the 80 km analysed. From the figure it can also be seen that the greatest changes have taken place close to the dam, with a 50% reduction in width over the first 20 km. The width has remained almost unchanged at a section close to the Lubambo tributary.

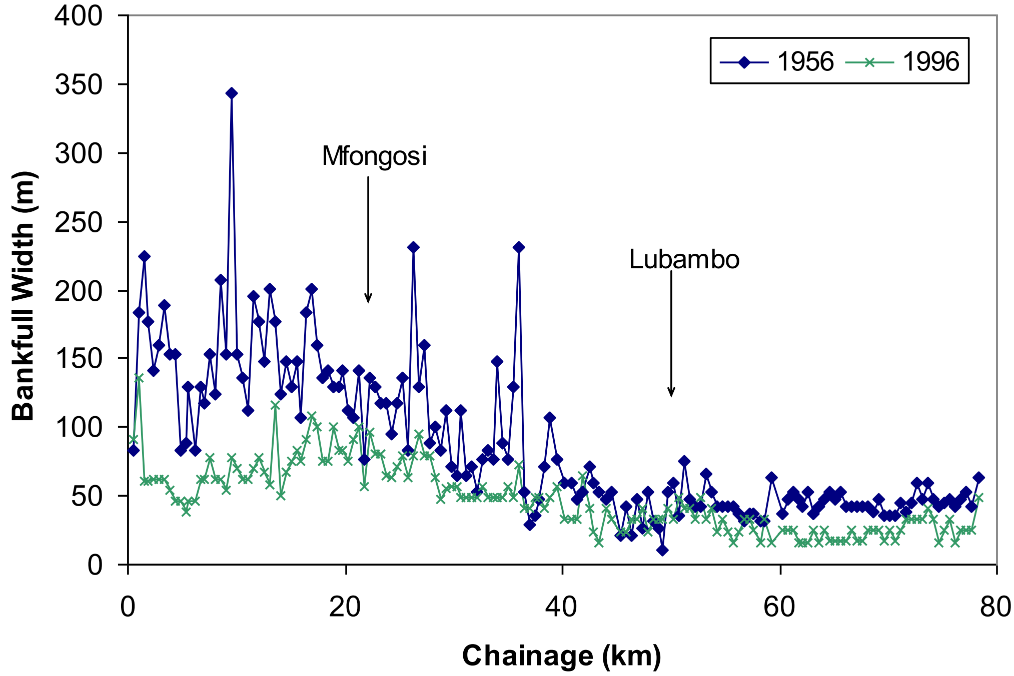


Figure 3.5-2 Changes in channel width of the Pongola River between 1956 and 1996 downstream of Pongolapoort Dam, South Africa (position of tributaries indicated)

3.6 Changes in Bed Material

Due to the decrease in magnitude and frequency of the high flows caused by a reservoir, the released flows are unable to transport the same amount and size of particles as before the dam was built. On the other hand the water released from a reservoir is usually clear and the flows are therefore able to entrain fine materials from the riverbed, while the coarser fractions in the bed are left behind. The relatively clear water releases can also be responsible for removing complete surface layers from the riverbed if they are composed of finer materials and thereby expose coarser layers.

Downstream of Hoover Dam on the Colorado River, USA, the median bed-particle diameter (d_{50}) increased from 0.2 mm to about 80 mm within seven years after closure of the dam (Williams and Wolman, 1984). Guanting Reservoir has had a similar but less dramatic effect on the bed material of the river. The median particle diameter d_{50} increased from 0.4 mm to about 7 mm (Chien, 1985). In the case of Hoover Dam the substantial increase in d_{50} was a result of the exposure of a layer of gravel, while the released flows downstream of Guanting Dam were not large enough to transport sizes greater than 5 mm. In the case of Glen Canyon Dam, not only was the annual fine sediment supply considerably reduced but also the seasonal pattern of storage and erosion (Topping *et al,* 2000)**.** The result is that newly input sand will only be in storage for about two months, unlike the nine months that it was stored on average before the dam was built.

Changes in mean particle size start taking place immediately after completion of a dam, but will reduce with time, because the availability of the fine materials decreases. Figure 3.6-1 shows the variation in mean particle diameter with time after dam closure below Parker Dam on the Colorado River, USA. The stabilization could have been the result of fine sediment input from tributaries or the uncovering of fine materials through erosion (Williams and Wolman, 1984).

The coarsening of the bed decreases with distance from a dam. This could be because further downstream tributaries again supply a certain amount of finer sediments, which could be deposited in the river channel. Another reason could be the decrease in bed degradation, which means that the likelihood of uncovering coarser materials is lower. Figure 3.6-2 shows this trend for Pongolapoort Dam, where d_{50} decreases from 1.7 mm to 0.17 mm over a distance of 60 km. Particle sizes were even bigger nearer the dam, with exposed bedrock at the dam. The mean particle diameter of 0.18 mm before the dam was built was estimated from particle size distributions of samples taken upstream of the dam (Kovacs *et al.*, 1985), such as that shown in Figure 3.6-2.

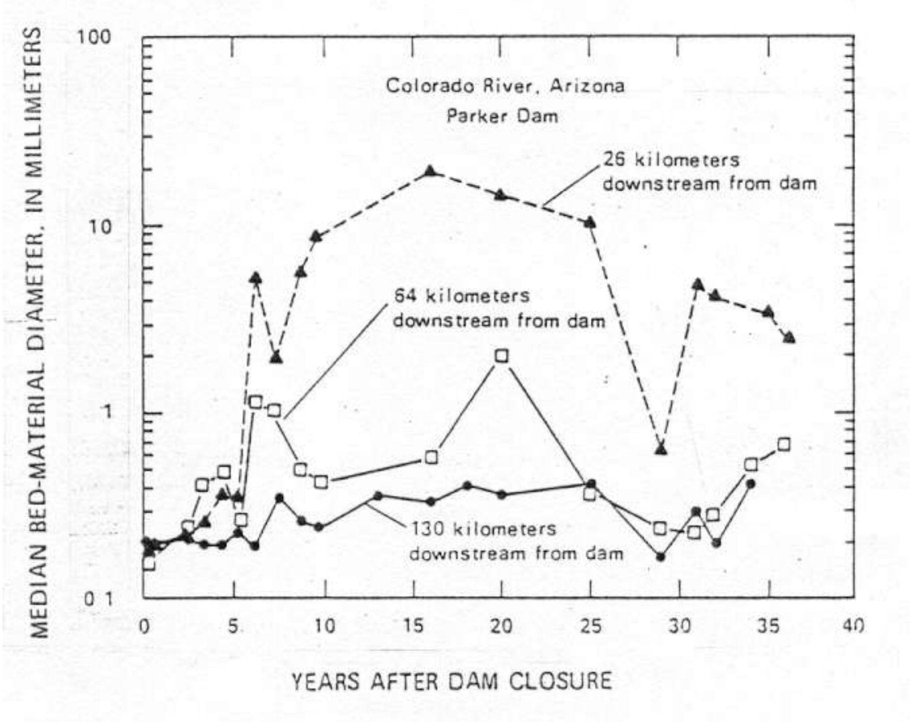


Figure 3.6-1 Variation of d50 downstream of Parker Dam, USA (Williams and Wolman, 1984)

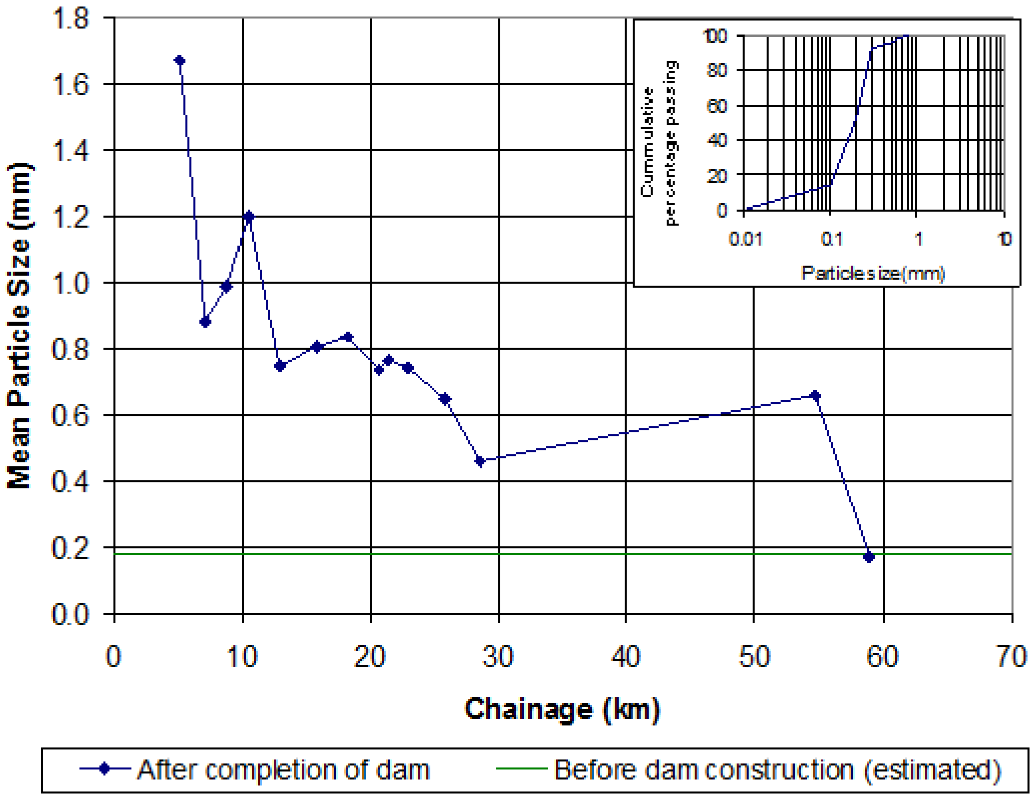


Figure 3.6-2 Variation of d_{50} downstream of Pongolapoort Dam, South Africa

As mentioned above, Sanmenxia Reservoir has had different modes of operation and the effect on the mean particle diameter is shown in **Figure 3.6-3**. During the flood detention phases muddy water was released after the floods had passed through the reservoir, whereas clear water was released during the storage periods. The reversal in trend was immediate, and the mean particle diameter remained relatively constant between 1964 and 1972.

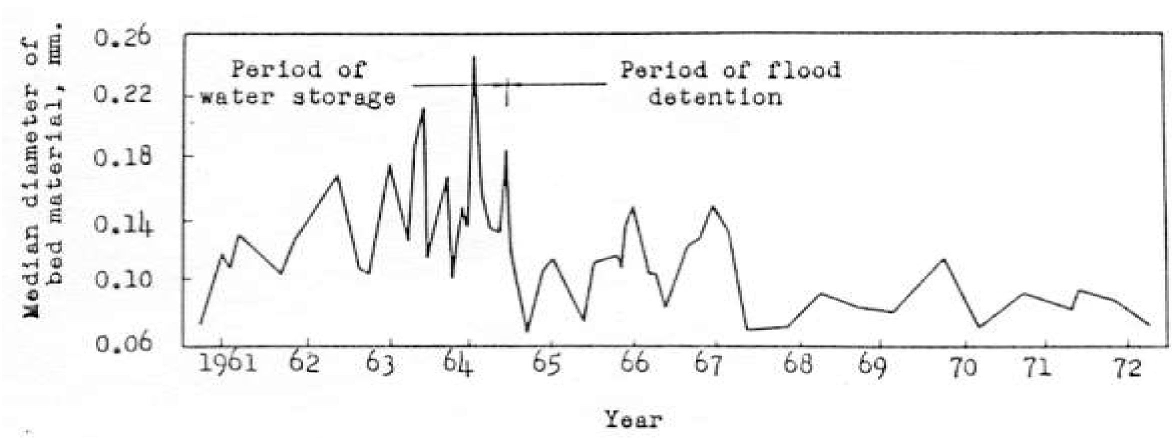


Figure 3.6-3 Variation of d50 downstream of Sanmenxia Dam, China, with different modes of operation (Chien, 1985)

Coarsening of the bed leads to an increase in roughness and a subsequent decrease in the transport capacity of the river. Chien (1985) reported that an increase in the mean particle diameter from 0.1 mm to 0.13 mm could reduce the transport capacity by 65%. Development of an armour layer is also important, because it controls degradation. On the Red River downstream of Dennison Dam, USA, 30 to 50% gravel cover limits degradation (Williams and Wolman, 1984). Schumm and Galay (1994) also reported that the Nile River has not degraded as much as expected downstream of the High Aswan Dam because of the coarse material being introduced by wadis along its length.

3.7 Changes in Slope and Channel Pattern

A reduced sediment load in a river channel downstream of a dam is associated with a decrease in transport capacity. This can be achieved by either increasing the bed roughness or by decreasing the channel slope. Flattening of the slope is usually only minor because it is easier to decrease the transport capacity by coarsening of the riverbed than by changing the slope (Chien, 1985). Large adjustments of the slope are difficult to achieve because the affected reach is usually very long and degradation would have to be considerable. In many cases the degree of degradation is also limited by the presence of bedrock, which is generally present below dam walls. In many cases there might therefore be no noticeable change in slope over a long reach, but on most rivers there could be small changes over shorter distances. On the other hand bed slope changes can also occur as a result of an increase in sinuosity (Williams and Wolman, 1984).

The Yong-ding River downstream of Guanting Dam shows virtually no change in slope over a 60 km distance. Six years after closure the bed was lowered by the same distance over the full distance (Chien, 1985). The same trend was observed downstream of the High Aswan Dam (Schumm and Galay, 1994), unlike the Colorado River below Glen Canyon Dam where the slope has decreased slightly within three years after the dam was built, and after that increased considerably as shown in Figure 3.7-1.

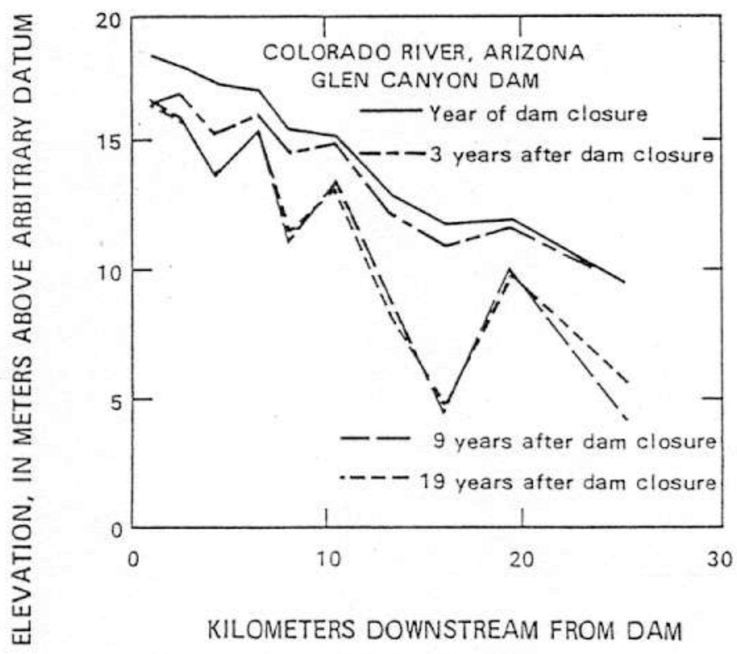


Figure 3.7-1 Changes in slope of the Colorado River below Glen Canyon Dam, USA (Williams and Wolman, 1984)

Since the bed profile downstream of a dam is dependent on factors like variations in bed material, water discharge, local controls and tributary contributions, the changes in slope along a certain reach are generally highly variable. This variability is evident downstream of Fort Randall Dam, Missouri River, where aggradation, degradation and no change occurred from one cross-section to another (Williams and Wolman, 1984).

A change in slope can be accompanied by a change in channel pattern. Leopold and Wolman (1957) have pointed out that the kind of channel pattern, which a river follows, depends amongst others on the channel slope. Braided rivers generally occur on steeper slopes than meandering rivers. As the river may adjust its slope in response to the construction of a dam, there may occur a corresponding change from braided to meandering or vice versa.

Chien (1985) reported that the river channel downstream of Naodehai Dam has become even more braided after the dam came into operation, while the effect of Sanmenxia Reservoir was a reduction in braiding during the impoundment phase due to severe degradation of the river bed (Zhou and Pan, 1994). The effect of the Lake Nasser on the relatively straight Nile River has not occurred as rapidly as for the two abovementioned examples, but Schumm and Galay (1994) reported that the thalweg has begun to show meandering tendencies over short reaches.

3.8 Changes in Vegetation

The reduced flows downstream of a dam will generally also reduce the frequency of overbank flooding, but at the same time the main channel can experience longer periods of low lows. The fact that the main channel carries water for longer periods encourages vegetation to grow closer to the channel. The reduced overbank flooding means that there is less overbank scouring and the vegetation will therefore develop a stronger hold.

The increased vegetation can block part of the river channel and thereby reduce the flow area and also trap sediments, which leads to aggradation of the bed. The vegetation can also increase bank stability due to the binding and protective effects of the vegetation (Williams and Wolman, 1984).

According to Schumm and Galay (1994) the bank erosion of the Nile River has in part been controlled by the growth of natural vegetation. The same was reported by Hadley and Emmett (1998) for Bear Creek, USA, downstream of Bear Creek Lake. The width increased only by 0.5 m over a period of 15 years, which they accredited to the growth of woody vegetation.

The increase in vegetation on the banks and floodplains leads to an increase in hydraulic roughness. This can result in higher flood levels.

3.9 Affected Distance

The river reach affected by a dam increases with time, until the river has adjusted to the new flow and sediment regime. The length of the reach affected by a dam depends on several factors. The location and number of major tributaries has a significant effect, as they are essential in replenishing both the sediment and water discharge, and the type of material they transport is also important. Andrews (1986) has reported for the Green River below Flaming Gorge Dam that tributaries have replenished the sediment supply within 68 miles (about 109 km).

Downstream base-level controls such as another reservoir or a weir can stop the progression of erosion, as can a reduction in transport capacity (either by a reduction in the slope or through coarsening of the bed material). All of these factors make it difficult to predict the exact extent of the affected reach. In the case of the Ash River, South Africa, only 15 km were affected by hydropower generation, partly as a result of the presence of a reservoir (Saulspoort Dam) 15 km downstream of the tunnel outlet. However, there were indications that just upstream of the dam the river was close to achieving an equilibrium state, which indicates that even without the dam the affected reach would probably not have been much longer.

Chien (1985) attempted to describe the process of degradation below a dam. The clear water released from the dam picks up sediment from the channel until the incoming load becomes equal to the sediment transporting capacity of the flow and the flow becomes saturated. This is called the point of concentration recovery and at the beginning of reservoir operation this also represents the point to which degradation progresses. After some time has elapsed, the bed material becomes coarser upstream of the point of concentration recovery, which means the transported sediment becomes coarser and the load becomes less than the transport capacity. On the other hand the coarsening of the bed material also results in a considerable reduction in the transport capacity of the flow. The result is that the point of concentration recovery actually moves towards the dam with time. However below the point of concentration recovery enough fine material still exists and the transporting capacity of the flow is larger than the incoming load. This results in further erosion and coarsening downstream. If the flow conditions remain unchanged the whole process will continue, causing degradation to extend far downstream of the dam. Chien however did not account for the effect of tributaries or downstream controls.

The length of the degraded reach below Hoover Dam was 120 km long, 13 years after closure, and there was no indication that the reach had stopped lengthening (Williams and Wolman, 1984). Below Sanmenxia Dam the affected distance was even longer at 480 km, as reported by Chien (1985). This is partly due to the fact that there are no major tributaries on the Yellow River below Sanmenxia Dam and it is feared that the whole river course of over 800 km could degrade over time.

3.10 Mitigating Measures

The release of artificial floods and flood flushing can be a viable option to restore and maintain the downstream river morphology that has been altered as a result of a dam, because the reduction of flood peaks and the trapping of sediment within the reservoir are two of the key factors affecting the extent of the dam's impact. Artificial flood releases and flood flushing design and operation have to be carefully planned and carried out, because poor management can have negative effects on the downstream river. Also many dams, due to their design, are not able to release artificial floods or to pass sediment, but if this is possible they could aid in restoring the natural sediment balance in the downstream river reach or at least maintain a desired state.

3.10.1 Managed Environmental Flood Releases

3.10.1.1 Glen Canyon Dam, USA

Glen Canyon Dam on the Colorado River, USA, (Figure 3.10-1) was completed in 1963 and flows have been regulated substantially since 1965. The primary purpose of the dam is to allocate runoff between several US states, with hydropower generation an incidental, though significant, purpose of the dam. The hydropower generation has caused large daily flow fluctuations, sometimes ranging between 109 m^3/s and 770 m^3/s, causing up to 4 m changes in the water surface elevation at some stations downstream of the dam (Andrews and Pizzi, 2000). The flow fluctuations have resulted in severe sand bar erosion as well as the establishment of dense exotic vegetation at the approximate elevation of the maximum power plant release. Sand slumps and liquefaction along the margins of the sand bars have been observed (Andrews and Pizzi, 2000). In 1992 operating restrictions were imposed, reducing the maximum release to 566 m^3/s (approximately 25% below power plant capacity) and restricting the maximum hourly changes in discharges for increasing and decreasing flows.

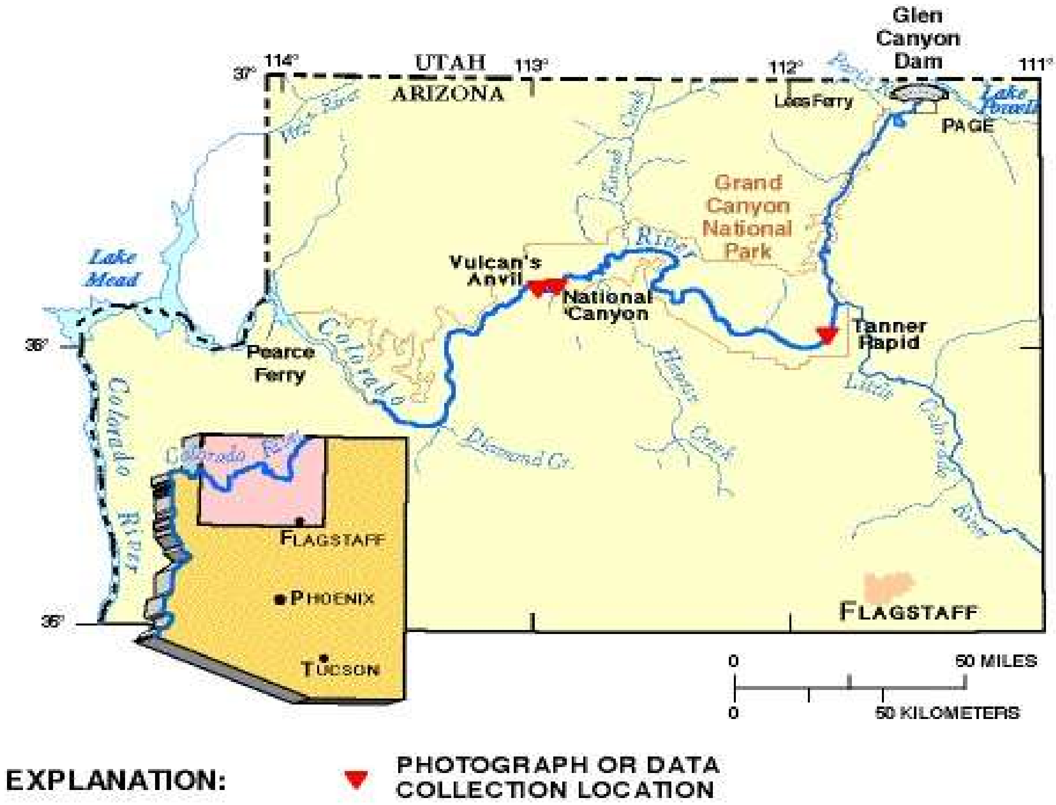


Figure 3.10-1 Glen Canyon Dam location (USGS, 2002b)

Glen Canyon releases essentially clear water. The pre-dam annual suspended sediment loads were 66 million ton at Lees Ferry gauging station (35 km downstream of Glen Canyon) and 86 million ton at Grand Canyon gauging station (a further 50 km downstream). The post-dam annual suspended sediment load at the Grand Canyon gauging station is approximately 25% of the pre-dam load. However, this decrease is not due to a lack of sediment, because the tributaries supply enough sediment, but because much of the sand is being deposited on the riverbed. The loss of the sandbars is not caused by an impoverishment of sand (Andrews and Pizzi, 2000).

During March and April of 1996 the first environmentally designed flood was released from Glen Canyon Dam. It was intended that the releases would restore and maintain the Colorado River's sediment sources through Grand Canyon, downstream of the dam, rebuild sandbars and simulate some of the dynamics of the river's pre-dam natural flow (Wegner, 1996). The flood was started at 225 m^3/s held constant for three days, after which it was built up to a maximum of 1275 m^3/s within 10 hours (Figure 3.10-2), which lasted for seven days after which the discharge was once again reduced to 225 m^3/s and held constant for three days (Figure 3.10-3). Surveys did show that sediment was mobilized from the bottom of the river channel and re-deposited along the river corridor in the Grand Canyon (see Figures 3.10-3 and 3.10-4). Another smaller flood (reaching 875 m^3/s, lasting for 48 hours) was released in November 1997. The reason for the flood was again to redistribute sediment along the riverside beaches in the Marble Canyon that had been deposited by summer high flows (USBR, 2002).

Future flood releases are planned to either protect the river sediment storage downstream or to reshape the river topography, redeposit sediment and enhance aquatic habitat. Future bar building releases will probably take place once every six years, when an uncontrolled spill is unlikely (Andrews and Pizzi, 2000).

Figure 3.10-2 Glen Canyon Dam 1275 m³/s flood release (USGS, 2002b)

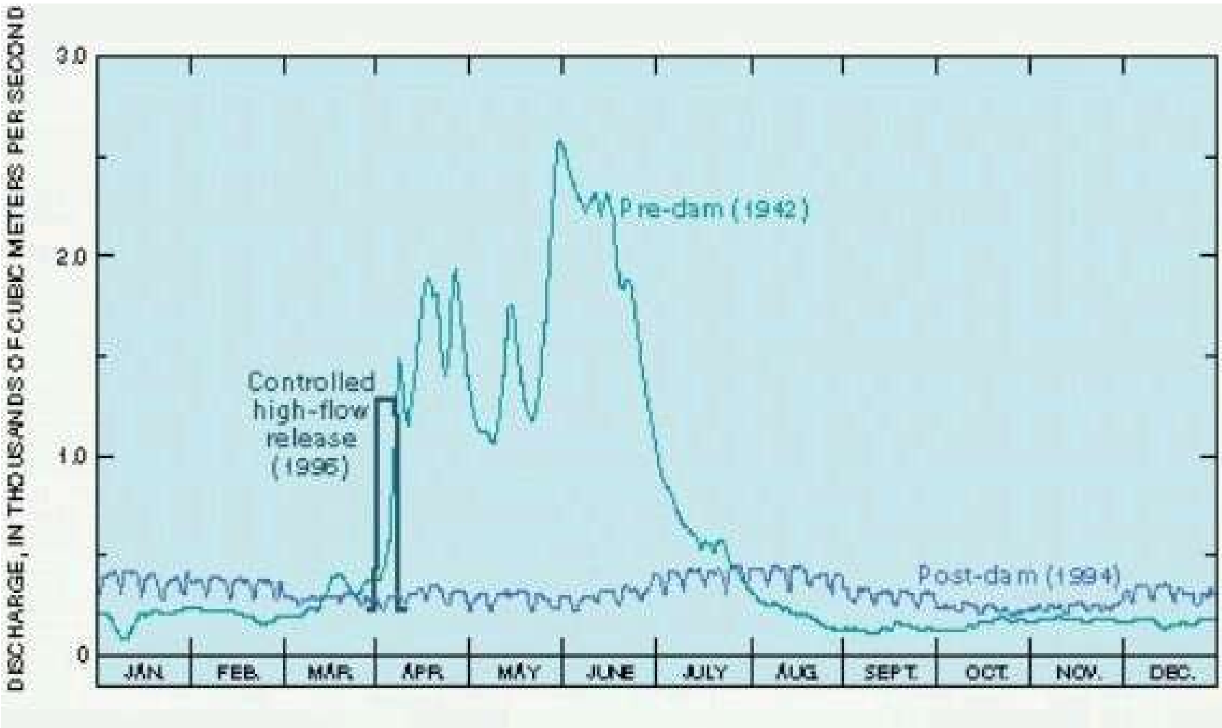


Figure 3.10-3 Relation of the controlled high flow release of 1996 to a typical snowmelt runoff hydrograph (1942) before dam construction and to typical power plant releases (1994) (USGS, 2002b)

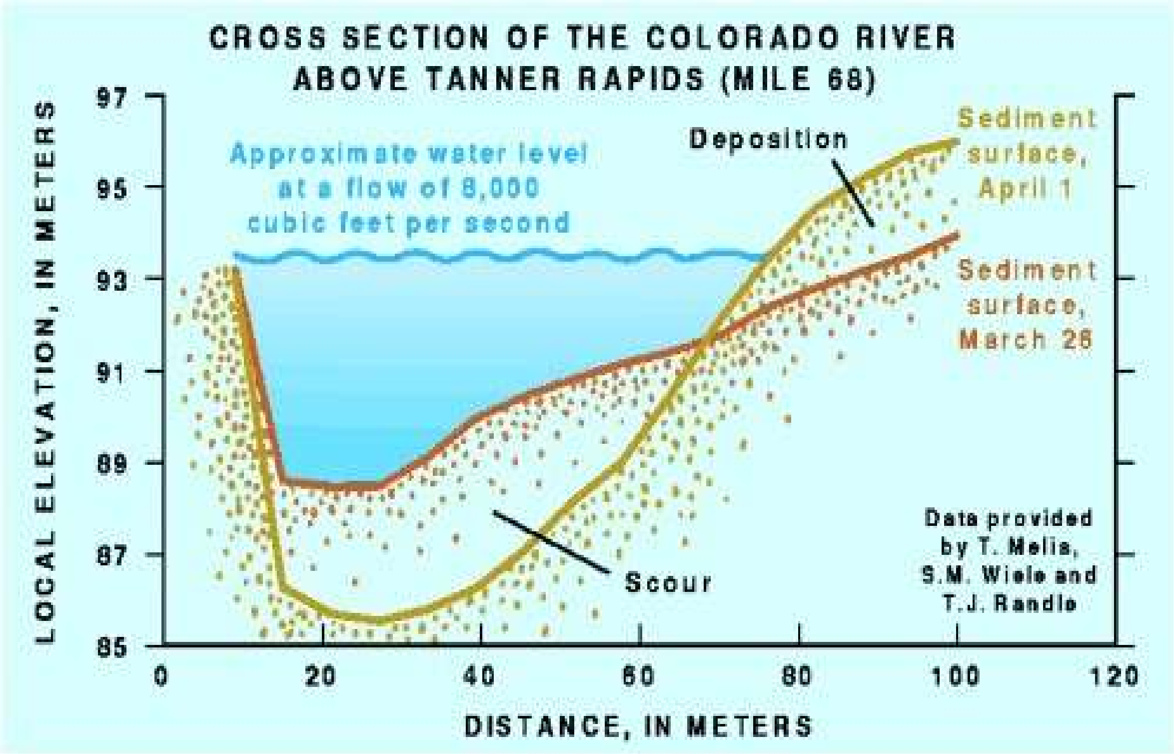


Figure 3.10-4 River cross-section changes above Tanner Rapids (USGS, 2002b)

Figure 3.10-5 Beach changes at National Canyon (Mile 166) at 255 m3/s and 340 m^3/s, respectively (USGS, 2002b)

3.10.1.2 Pongolapoort Dam, South Africa

Managed flood releases have been made from Pongolapoort Dam on the Pongola River, South Africa, since the mid 1980's, once or twice a year (Figure 3.10-6). The volume and peak discharge that can be released depend to a large degree on whether these floods will cause damages to low-lying agricultural lands and dwellings in Mozambique (the border between South Africa and Mozambique is just over 100 km downstream of Pongolapoort Dam). The volume released has varied between about 70 and 600 million m^3, with peak discharges of between 300 and 800 m^3/s. The main reasons for these flood releases were to draw down the water level in the reservoir in anticipation of the coming rainy season, as well as to recharge many of the pans downstream of the dam and provide water for the fish habitats, on which the local population depends. In recent years field investigations have been carried out during these flood releases to determine what geomorphological effect these floods have had on the Pongola River and to determine whether they could be improved upon in terms of the magnitude, frequency and timing of these flood releases.

Figure 3.10-6 Pongolapoort Dam managed environmental flood release

3.10.2 Flood Flushing of Sediments

3.10.2.1 Sanmenxia Dam, China

The Yellow River in China has one of the highest sediment loads in the world, which makes it essential to operate the reservoirs correctly. Sanmenxia Dam on the Yellow River, China, was built initially for year-round impoundment, but after severe sedimentation occurred in the reservoir, the operation was changed to flood detention. In 1964 and 1969 the outlet works were reconstructed (Figure 3.10-7) so that the reservoir can now be operated for sediment sluicing, flood control and hydropower. Clear water is stored in the non-flood season and muddy water released in the flood season (Figure 3.10-8), thereby the reservoir capacity is maintained and the sediment transport capacity of the downstream river channel increased (Qian *et al*., 1993). Before the reservoir operation was changed, severe aggradation occurred in the downstream river due to the reduced flood peaks. Now only major floods are detained and the smaller floods together with the sediment load and previous deposits are released. The outflow varies between 2000 and 6000 m^3/s, with a maximum mean daily discharge of 8000 m^3/s. The channel aggradation was alleviated.

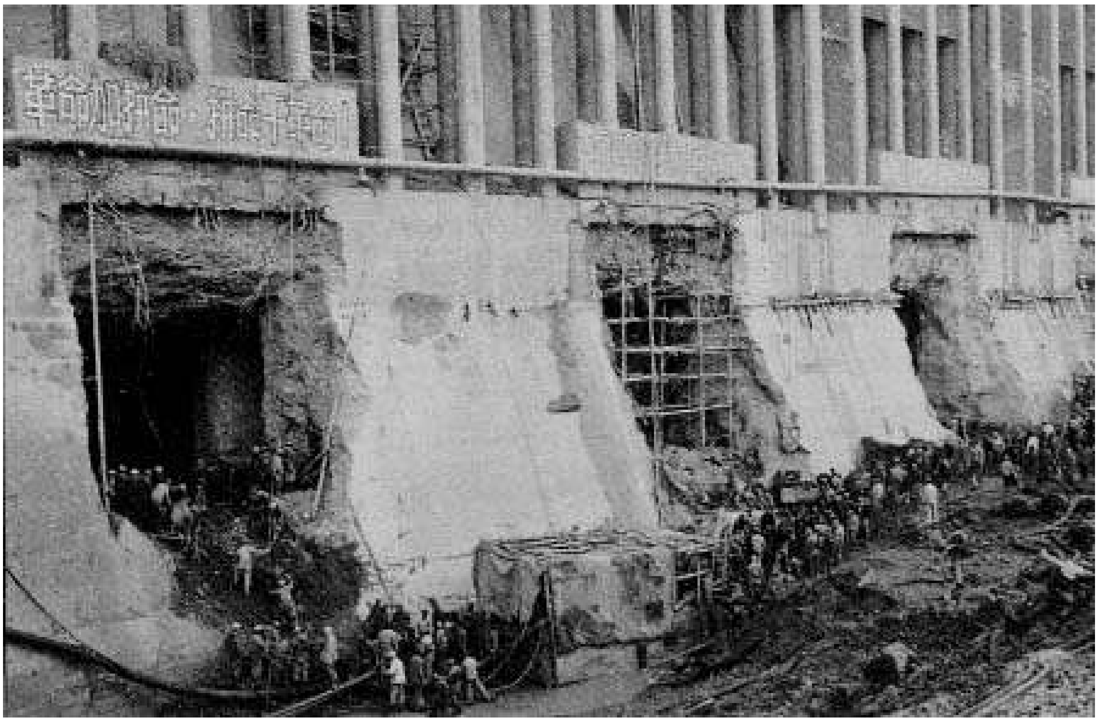


Figure 3.10-7 Reconstruction of the bottom outlets at Sanmenxia Dam

Figure 3.10-8 Sediment flushing at Sanmenxia Dam (side outlet)

Tributaries still pose a large threat in that they carry large quantities of sediment, which could block the main channel. In 1966 a small flood (peak discharge 3660 m^3/s) from one of the tributaries in the upper reaches of the Yellow River carrying around 16.5 million ton of sediment (runoff was around 23 million m^3), blocking the main channel of the Yellow River for a short while. Should the discharge of the main river have been regulated, the blockage would have been more serious and the discharge necessary to break the blockage would have been much greater.

4. River Channel Morphology

A natural river is never completely stable because of the natural variability of the factors that control the morphology especially the water discharge and sediment load. Even though the variability can be great, as is the case in the semi-arid climate, a river will strive to attain a state of dynamic or quasi-equilibrium, by changing its cross-section, slope and even channel pattern to obtain optimal transport of water and sediments. Such a river is said to be in regime, meaning that it has obtained a long-term stable configuration, with only minor adjustments. Major changes tend to only occur as a result of significant events like a 1:100-year flood or the construction of a dam.

In order to analyse the effects that a dam can have on the downstream river channel, it is important to be able to describe the stable river morphology. There are two approaches to describing the hydraulic geometry of alluvial rivers: the empirical approach and the theoretical or analytical approach. The empirical approach attempts to derive relationships from available data and is thus dependent on the quality of the data. The theoretical or analytical approach relies on fundamental hydraulic processes like flow resistance and sediment transport, where the identification of the dominant processes is very important. A first attempt is generally the development of empirical regime equations that provide at least an indication of the direction of the changes. Regime equations based on hydraulic processes occur in very much the same format as the empirical equations, with the same input variables. The one difference is that the theoretical/analytical regime equations are generally applicable to a wider range of conditions. Another way of describing the channel geometry is through some form of extremal hypothesis, e.g. the minimization of stream power approach by Chang (1979, 1988).

A river has at least three degrees of freedom in its width, depth and slope, while Chang (1979) added the channel pattern to the list. The velocity is not regarded as a degree of freedom because it is determinable from the discharge and channel geometry. The factors that control or influence these variables are the water discharge, sediment load, and bed and bank materials. The water and sediment discharge are by far the most dominant factors also as a result of their great variability. The bed and bank materials remain relatively unchanged under stable conditions, and generally only change as a result of a change in water and sediment discharge. This is also why dams have such far-reaching impacts on a river, because they disturb the flows and sediment load to such a high degree.

4.1 Dominant Discharge

The water discharge is by far the most important parameter responsible for the geometrical shape of a channel and it is obvious that identifying the correct discharge is of utmost importance. Although a whole range of flows normally shapes a river, there is a general consensus that one steady flow rate, the dominant discharge, should produce the same channel dimensions as a sequence of events. This channel-forming discharge can be defined as either the flow rate that determines particular channel parameters or that cumulatively transports the most sediment.

Many researchers have equated the dominant discharge with the bankfull discharge. Bankfull discharge is the flow rate that just fills the channel to the tops of the banks, corresponding to the condition of incipient flooding. Ackers (1988) argued that sediment transport would decrease once the flow goes overbank, because of an increase in overall resistance and reduction in erosive tendencies of the flow, while Ackers and Charlton (1970) found that the bankfull discharge works best for describing sinuosity and meander wavelength. Carling (1988) reasoned that at bankfull level the resistance to flow is a minimum and the sediment transport rate a maximum. The dominant discharge has also been linked to a recurrence interval of approximately 1-2 years by several researchers (Harvey, 1969), but most of these studies actually established a much wider range for bankfull flow recurrence intervals between 1 and 10 years.

There are several problems regarding the use of bankfull discharge as the dominant discharge. The biggest is that there exist numerous definitions of the bankfull level, as Williams (1978) pointed out. These include either the elevation of certain benches or the active floodplain, the lower boundary of perennial vegetation or the elevation at which the width/depth ratio becomes a minimum. The determination of the discharge corresponding to the bankfull elevation presents an additional problem. The most common ways of determining this discharge are by means of a rating curve, hydraulic geometry or flow equations. Considering all the different approaches it is not surprising that by comparing the various methods, Williams (1978) obtained a wide range of results, in most cases varying by more than 100%. He also observed that obtaining a bankfull discharge at one cross-section is questionable since it can be radically different a few meters upstream or downstream.

In regions with highly variable runoff the bankfull discharge may not represent the dominant discharge because the water rarely flows at bankfull for long periods of time. The assumptions of a return period of 1 – 2 years also does not hold true in drier climates, because these floods are not nearly large enough to shape a channel extensively. On the other hand large floods have the capacity to reshape the channel geometry, but they occur too infrequently to have a lasting effect and the river changes back to a more stable channel. Wolman and Miller (1960) observed that the greater the variability in runoff, the larger the percentage of sediment carried by infrequent floods, which means the dominant discharge is bound to have a longer recurrence interval than 1 - 2 years. Osterkamp and Hedman (1979) studied ephemeral rivers and found that their widths are more indicative of more unusual discharges than the mean discharge. They related the channel width of ephemeral streams to the 1:10-year flood. Clark and Davies (1988) also found that the dominant discharge had an average return period of 10 years.

For the bankfull discharge to actually occur at bankfull level, means that the river channel must have already adjusted to accommodate that flow, because as soon as the flow regime changes the frequency of the former bankfull discharge will either increase or decrease depending on the changes in regime. This means that the former bankfull discharge will not have the same effects as before and that a different "bankfull" discharge with a different magnitude will emerge. If this is smaller than the original bankfull discharge, the channel will be too big and the "bankfull" discharge will actually not fill the channel to the top of the banks. On the other hand if the flows should increase in magnitude the "bankfull" discharge will actually flow over the banks. The river channel will adjust to the changed flow regime and it will thus take a while before the "bankfull" discharge will actually flow at bankfull level, and only then will it have reached its full effectiveness. Considering that the bankfull discharge has been related to the dominant discharge, because of the extraordinary conditions at bankfull level, i.e. maximum sediment transport rate, the bankfull discharge is a misleading concept in the formation of a river channel's geometry, while it might be more likely to maintain a river channel once it has adjusted to a new flow regime.

When establishing mathematical or analytical tools describing the changes in channel geometry after the construction of a dam, it might be more correct to use a discharge that can actually be predicted with accuracy. Although it is difficult to link the dominant discharge to a specific recurrence interval, it seems that for a arid and semi-arid regions the river channels are formed by discharges that occur rather infrequently, with a recurrence interval between 5 and 20 years.

4.2 Existing Regime Equations

Regime equations have been used to describe river channel geometry for over a century, starting with the first attempts by Kennedy for irrigation canals in 1895. Further attempts were made by Lacey and Blench on straight canals, both having incorporated factors relating to sediment transport. Leopold and Maddock were among the first to develop regime equations for straight alluvial rivers. Later attempts were made to extend the equations to gravel-bed rivers, as well as to meandering rivers.

These regime equations were all empirically derived. The problem with the empirical regime equations is that they are only applicable to the range of conditions for which they were derived. Analytically or theoretically derived regime equations on the other hand are applicable to a wide range of conditions. Nonetheless it is important to correctly identify the dominant processes involved in the formation of a stable channel geometry. Since these processes are rather complex, it is mostly necessary to simplify the equations by deriving coefficients empirically, leading to semi-theoretical or semi-analytical regime equations.

4.1.2 Width Equations

The width generally shows the greatest adjustment after a change in flow regime, and some of the regime equations that have been derived are summarised in **Table 4.2.1-1**, which shows that most equations are expressed only in terms of discharge. This is because the water discharge is by far the most important factor influencing the channel geometry. From the summarised equations the following qualitative observation can be made regarding the effects of changing input variables on the channel width (**Table 4.2.1-2)**. A plus or minus exponent denotes an increase or decrease in the variable considered (Schumm, 1969).

Table 4.2.1-1 Effect of changing input variables on channel width

Input variable	Input variable change	Associated change in B
Q	+	+
	-	-
D	+	+
	-	-
S	+	-
	-	+

with Q = discharge

B = channel top width

d = particle size

S = channel slope

An increase in discharge will thus lead to an increase in width due to its increased erosive tendency, while an increase in the particle size leads to a decrease in channel width because coarser particles are more difficult to erode. Usually the change in particle size is related to the change in discharge, so both will change together. The coarsening of the bed material may thus be a way for the river to counteract the effect of the increasing discharge. Considering that the exponent of discharge in the width equations is generally close to 0.5 and thereby almost twice as large as the particle size exponent, which is usually less than –0.2, the effect of a change in discharge will outweigh a change in particle size.

Most of the variables under consideration will not change in isolation, but rather in response to, or together with another variable. An increase in discharge, which causes channel widening, is generally accompanied by a decrease in slope. Thus a decrease in slope can be associated with an increase in width. The same principle applies to an increase in sediment concentration, which is a consequence of an increase in discharge. A widening of the river channel can therefore be expected when the sediment concentration increases in this way.

Table 4.2.1-2 Summary of width equations (adapted from Wargadalam, 1993)

Author	Equation	Units	Remarks
Lacey (1930)	$P = 2.667\ Q^{0.5}$	ft	Bankfull discharge, sand-silt canals
Blench (1957)	$B = b\ Q^{0.5}\ d^{0.25}$	ft	Bankfull discharge, sand-silt canals, $d = d_{50}$ (mm), $b = \sqrt{(1.9(1 + 0.012C)/F_s)}$
Leopold & Maddock (1953)	$B = a\ Q^{0.5}$	ft	Bankfull discharge, alluvial rivers, *a* varies for individual streams
Henderson (1963)	$B = 0.93\ Q^{0.46}\ d^{-0.15}$	ft	Design discharge, narrow channels, $d = d_{50}$
Kellerhals (1967)	$B = 1.8\ Q^{0.5}$	ft	Dominant discharge, gravel-bed rivers
Chitale (1966)	$P = 2.187\ Q^{0.523}$	ft	Sand-silt canals
Bray (1982)	$B = 2.38\ Q^{0.527}$	ft	1:2-year discharge, gravel-bed rivers
Bray (1982)	$B = 2.08\ Q^{0.528}\ d^{-0.07}$	ft	1:2-year discharge, $d = d_{50}$, gravel-bed rivers
Hey & Thorne (1986)	$B = k_1\ Q^{0.5}$	m	Bankfull discharge, gravel-bed rivers, k_1 = f(bank vegetation)
Nouh (1988)	$B = 28.30\ (Q_{50}/Q)^{0.83} + 0.018\ (1 + d)^{0.93}\ C^{1.25}$	m	Mean annual discharge, $d = d_{50}$, ephemeral channels (arid zone)
Julien & Wargadalam (1995)	$B = 0.512\ Q^{\alpha}\ d_s^{\beta}\ S^{\gamma}$	m	Dominant discharge, $\alpha = (2 + 4m)/(5 + 6m)$, $\beta = -4m/(5 + 6m)$, $\gamma = (-2m - 1)/(5 + 6m)$, $m = 1/\ln(12.2D/d_s)$

4.2.2 Depth Equations

The depth is generally the first to change when the natural flows of a river are altered. The magnitude of this change is not as considerable as that of the width, because the depth can be controlled to a much larger degree by armouring or the exposure of bedrock.

A summary of some depth equations is provided in **Table 4.2.2-1.** The same variables that determine the width also describe the depth. Although the discharge is still the most important factor, more equations describe the depth in terms of discharge and particle size, meaning that the particle diameter has a greater effect on the depth than the width. From the summarised equations the following observation can be made regarding the effects of changing input variables on the channel depth (**Table 4.2.2-2**).

Table 4.2.2-1 Effect of changing input variables on channel depth

Input variable	Input variable change	Associated change in D
Q	+	+
	-	-
d	+	-
	-	+
S	+	-
	-	+

with *D* = channel depth

Much the same patterns can be observed here as those that were encountered for the width equations. A deeper channel can occur as a result of an increased discharge, coarser bed material or a decrease in channel slope. The one difference is that a river channel becomes deeper with a decrease in sediment concentration. A decreasing sediment concentration signifies that the transport capacity of the flow is not fully utilised and more sediment will be picked up from the bed, leading to a deeper river channel.

Table 4.2.2-2 Summary of depth equations (adapted from Wargadalam, 1993)

Author	Equation	Units	Remarks
Lacey (1930)	$R = 0.405\ Q^{0.333}\ d^{-0.167}$	ft	Bankfull discharge, sand-silt canals
Blench (1957)	$D = c\ Q^{0.333}\ d^{-0.333}$	ft	Bankfull discharge, sand-silt canals, $d = d_{50}$ (mm), $c = [F_s/(1.9(1 + 0.012C))]^{0.333}$
Leopold & Maddock (1953)	$D = b\ Q^{0.3}$	ft	Bankfull discharge, ephemeral streams, *b* varies for individual streams
Henderson (1963)	$R = 0.12\ Q^{0.46}\ d^{-0.15}$	ft	Design discharge, narrow channels, $d = d_{50}$
Kellerhals (1967)	$D = 0.166\ Q^{0.4}\ k_s^{-0.12}$	ft	Dominant discharge, gravel-bed rivers, $k_s = d_{90}$
Chitale (1966)	$R = 0.486\ Q^{0.341}$	ft	Sand-silt canals
Bray (1982)	$D = 0.266\ Q^{0.333}$	ft	1:2-year discharge, gravel-bed rivers
Bray (1982)	$D = 0.256\ Q^{0.331}\ d^{-0.025}$	ft	1:2-year discharge, $d = d_{50}$, gravel-bed rivers
Hey & Thorne (1986)	$D = 0.22\ Q^{0.37}\ d^{-0.11}$ $R = k_3\ Q^{0.41}\ Q_s^{0.02}\ d^{-0.14}$	m	Bankfull discharge, $d = d_{50}$, gravel-bed rivers, k_3 = f(bank vegetation)
Nouh (1988)	$R = 1.29\ (Q_{50}/Q)^{0.65} - 0.01\ (1 + d)^{0.98}\ C^{0.46}$	m	Mean annual discharge, $d = d_{50}$, ephemeral channels (arid zone)
Julien & Wargadalam (1995)	$D = 0.2\ Q^{\alpha}\ d_s^{\beta}\ S^{\gamma}$	m	Dominant discharge, $\alpha = 2/(5 + 6m)$, $\beta = 6m/(5 + 6m)$, $\gamma = -1/(5 + 6m)$, $m = 1/\ln(12.2D/d_s)$

4.2.3 Slope Equations

Apart from changes in width and depth an alluvial river can also change its slope in response to an altered flow regime. A change in channel slope can have far reaching consequences as it can be accompanied by a change in channel pattern, but it usually takes much longer for an appreciable change in slope than a change in width or depth to become evident, which means that changes in channel pattern may take even longer to occur.

Table 4.2.3-1 gives an overview of some slope equations. As with the width and depth, discharge and particle size are the two dominant variables that determine the slope. Generally however the slope equations have very poor coefficients of determination.

Table 4.2.3-1 Effect of changing input variables on channel slope

Input variable	Input variable change	Associated change in S
Q	+	-
	-	+
d	+	+
	-	-

As mentioned before, the relationship between discharge and channel slope is such that as the discharge decreases the slope becomes steeper, which also follows from the slope equations in **Table 4.2.3-2**. This occurs because the transport capacity of the river channel decreases as the discharge is reduced and the increase in channel slope is a measure to increase the transport capacity again. The particle size *d* on the other hand is directly proportional to the slope. This probably is due to the fact that on steeper slopes the transport capacity increases and most of the finer material is washed away. Judging by the magnitude of the particle size exponent, *d* also plays a much greater role in determining the slope than the depth or width. Although in this case it is more likely that the slope determines the particle size, whereas the depth and width are definitely influenced by the particle size.

Table 4.2.3-2 Summary of slope equations (adapted from Wargadalam, 1993)

Author	Equation	Units	Remarks
Lacey (1930)	$S = 0.00118\ Q^{-0.167} d^{0.833}$	ft	Bankfull discharge, sand-silt canals
Leopold & Maddock (1953)	$S = a\ Q^{-0.95}$	ft	Bankfull discharge, ephemeral streams, *a* varies for individual streams
Henderson (1963)	$S = 0.44\ Q^{-0.46} d^{1.15}$	ft	Design discharge, narrow channels, $d = d_{50}$
Kellerhals (1967)	$S = 0.12\ Q^{-0.4}\ k_s^{-0.92}$	ft	Dominant discharge, $k_s = d_{90}$
Chitale (1966)	$S = 0.0005\ Q^{-0.165}$	ft	Sand-silt canals
Bray (1982)	$S = 0.0354\ Q^{-0.342}$	ft	1:2-year discharge, gravel-bed rivers
Bray (1982)	$S = 0.0965\ Q^{-0.334}\ d^{0.586}$	ft	1:2-year discharge, $d = d_{50}$, gravel-bed rivers
Hey & Thorne (1986)	$S = 0.087\ Q^{-0.43}\ Q_s^{0.1}\ d_{50}^{-0.09}\ d_{84}^{0.84}$	m	Bankfull discharge, gravel-bed rivers,
Nouh (1988)	$S = 18.25\ (Q_{50}/Q)^{-0.35} - 0.88\ (1+d)^{1.13}\ C^{0.36}$	m	Mean annual discharge, $d = d_{50}$, ephemeral channels (arid zone)
Julien & Wargadalam (1995)	$S = 12.4\ Q^{\alpha}\ d_s^{\beta}\ S^{\gamma}$	m	Dominant discharge, $\alpha = -1/(3 + 2m)$, $\beta = 5/(4 + 6m)$, $\gamma = (5 + 6m)/(4 + 6m)$, $m = 1/\ln(12.2D/d_s)$

The reason for the poor coefficients of determination of most slope equations may be that the slope takes so much time to adjust to the altered flows and that it may only change over short distances. The measured field slopes might therefore not be equilibrium slopes, making it incorrect to use them in calibration or verification processes.

4.3 Proposed Regime Equations for Semi-arid Conditions

In this section a set of regime equations for semi-arid rivers are presented, based on a recurrence interval flood replacing the dominant/bank full discharge.

Following a calibration on South African and validation against USA data, the following regime equations are proposed for use in semi-arid regions (MAP< 600 mm/a).

$$B = 4.034 Q_{10}^{\ 0.365} S^{-0.228} d_{50}^{\ 0.053} \qquad (4.3\text{-}1)$$

$$D = 0.071 Q_{10}^{\ 0.374} S^{-0.154} d_{50}^{\ -0.02} \qquad (4.3\text{-}2)$$

where B (m), D (m), Q (m^3/s), S (m/m), d_{50} (m)

All the width equations were first calibrated for four peak discharges with recurrence intervals of 2, 5, 10 and 20 years using the corresponding top widths. The 1:10-year discharge gave the best coefficients of determination for all cases. This would mean that the 1:10-year discharge is the discharge that has the dominant impact on the channel morphology. All further calibrations are therefore carried out with Q_{10} as the dominant discharge. The range of values of each parameter used in the calibration is shown in **Table 4.3-1.**

Table 4.3-1 Variability of channel parameters

Parameter	Range
Discharge Q_{10} (m^3/s)	68 – 5200
Width B (m)	22 – 351
Average Depth D (m)	0.51 – 5.90
Hydraulic Radius R (m)	0.49 – 6.40
Slope S	0.00015 – 0.07198
d_{50} (mm)	0.005 – 0.5

It should be remembered that these equations only predict the average width and depth, whereas these two variables can vary considerably from one section to another on a river. For the rivers under consideration, it was found that on average the widths could be 30% larger or smaller than the average width over a certain river reach. This means that a river with an average width of 100 m is likely to be between 70 and 130 m wide. For the depths a slightly smaller variation of 20% was established.

In addition to the coefficient of determination it is sometimes useful to express the accuracy of the relationships in terms of their ability to predict the width and depth within certain accuracy ranges, as indicated in **Tables 4.3-2** and 4.3-3.

Table 4.3-2 Accuracy of new width relationships

Equation	$0.67 < \frac{B_{calculated}}{B_{observed}} < 1.5$	$0.5 < \frac{B_{calculated}}{B_{observed}} < 2$	$0.33 < \frac{B_{calculated}}{B_{observed}} < 3$
3.3.9	75 %	97 %	100 %

Table 4.3-3 Accuracy of new depth relationships

Equation	$0.67 < \frac{D_{calculated}}{D_{observed}} < 1.5$	$0.5 < \frac{D_{calculated}}{D_{observed}} < 2$	$0.33 < \frac{D_{calculated}}{D_{observed}} < 3$
3.3.10	90 %	98	100

4.3.1 Comparison and Verification

In order to establish the applicability of the new regime equations they are verified using an independent set of data, as well as comparing them to the semi-theoretical channel geometry equations developed by Julien and Wargadalam (1995). These are applicable to a very wide range of conditions, since they are theoretically based and also calibrated on an extensive set of data. The semi-theoretical relations are as follows:

$$B = 1.33Q^{(2+4m)/(5+6m)} d_{50}^{-4m/(5+6m)} S^{-(1+2m)/(5+6m)} \tag{4.3-3}$$

$$D = 0.2Q^{2/(5+6m)} d_{50}^{6m/(5+6m)} S^{-1/(5+6m)} \tag{4.3-4}$$

$$m = \frac{1}{\ln\left(\frac{12.2D}{d_{50}}\right)}$$

where (4.3-5)

The data set used for the comparison is taken from Wargadalam (1993). It consists of 28 sets of data from various sand bed rivers.

These two equations are very similar to the regime equations proposed for semi-arid and the computed widths are almost identical as shown in Figure 4.3-1. It does seem though that Equation overestimates the depth considerably as shown in Figure 4.3-2. The fact that the semi-theoretical channel geometry equations by Julien and Wargadalam (1995) and the semi-arid regime equations generally produce similar results and also have similar accuracy ranges, give **Equations** and a sound basis.

The same data is used to verify **Equations** and as with the calibration process the accuracy of the new regime equations are expressed in terms of their ability to predict data within certain accuracy ranges, shown in **Table 4.3-4** and 4.3-5.

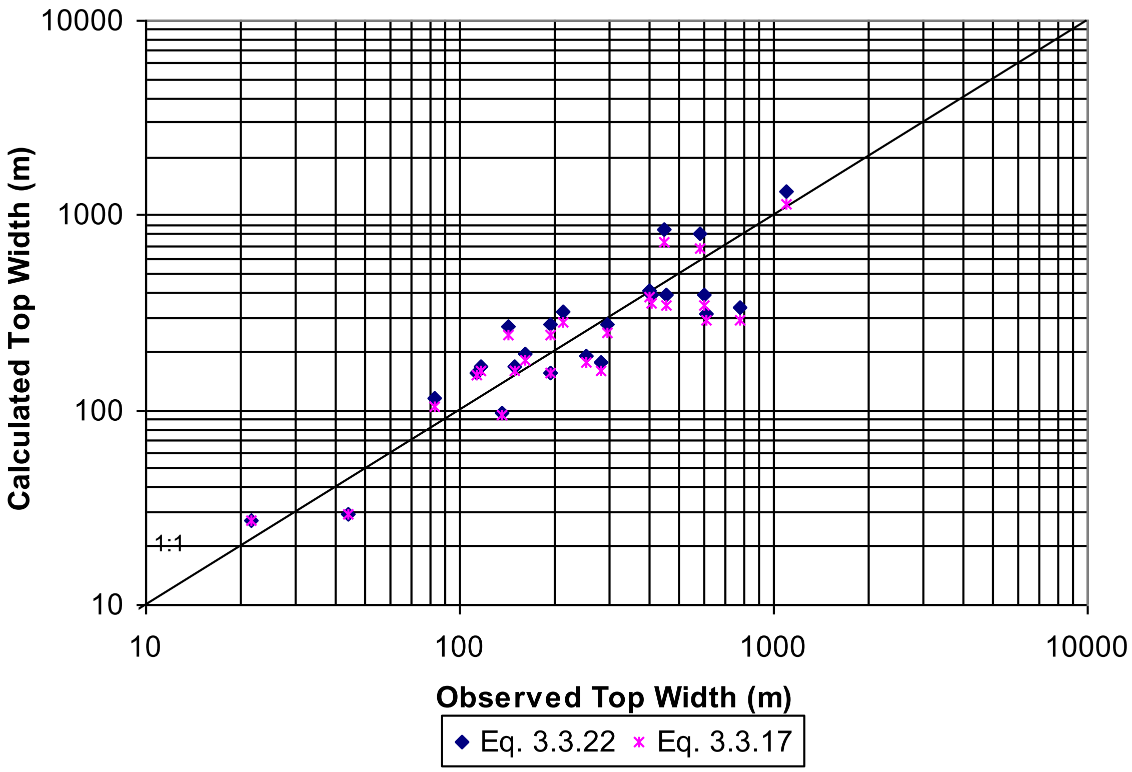


Figure 4.3-1 Comparison of existing and new width equations

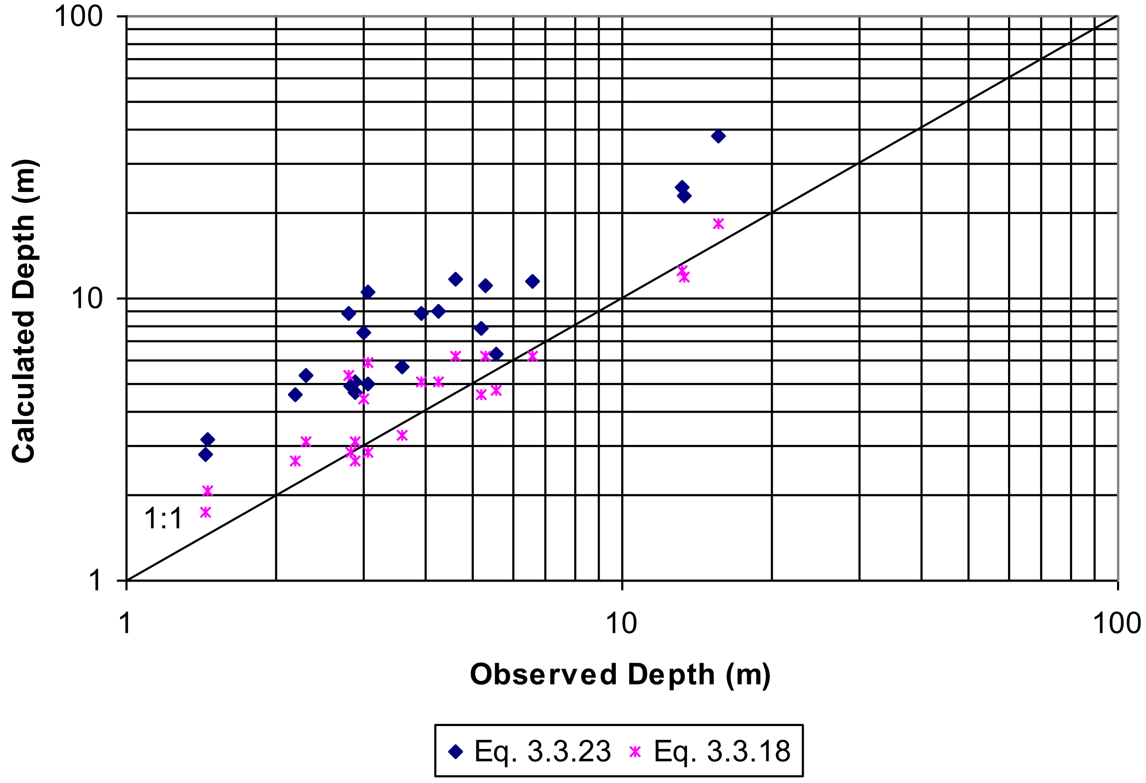


Figure 4.3-2 Comparison of existing and new depth equations

Table 4.3-4 Accuracy ranges of width relationships (independent river data)

Equation	$0.67 < \frac{B_{calculated}}{B_{observed}} < 1.5$	$0.5 < \frac{B_{calculated}}{B_{observed}} < 2$	$0.33 < \frac{B_{calculated}}{B_{observed}} < 3$
New	64 %	79 %	96 %
Julien, et al.	61 %	89 %	100 %

Table 4.3-5 Accuracy ranges of depth relationships (independent river data)

Equation	$0.67 < \frac{D_{calculated}}{D_{observed}} < 1.5$	$0.5 < \frac{D_{calculated}}{D_{observed}} < 2$	$0.33 < \frac{D_{calculated}}{D_{observed}} < 3$
New	82 %	100 %	100 %
Julien, et al.	54 %	93 %	100 %

Tables 4.3-4 and 4.3-5 show very much the same trends as Tables 4.3-2 and 4.3-3, except that the accuracies are sometimes lower, which is to be expected because of the use of independent data in the verification process. However the accuracies are still good and compare well to the accuracies of Julien and Wargadalam's relations.

.4.4 Channel Patterns

Apart from the width, depth and channel slope, a river can also adjust its channel pattern in response to imposed changes in the flow regime and sediment load. The three major patterns are straight, meandering and braided, which are very much linked to the channel slope. There exist several thresholds or discontinuities between these channel patterns and if the channel slope should be close to the critical or threshold slope, the river pattern can change. A small change in channel slope can therefore lead to a definite change in river pattern.
An index used to describe the channel planform is the sinuosity, defined as the ratio of channel length to valley length. Leopold and Wolman (1957) have stated that a reach could be considered meandering when the sinuosity is greater than or equal to 1.5. The value is arbitrary, but they argued that a sinuosity of 1.5 indicates a truly meandering river. Chang (1988) as well as other researchers have adopted that value.

The channel patterns and their relationships with the channel slope can therefore be identified as follows:

- Truly straight rivers (sinuosity < 1.1), rarely occurring in nature and are usually artificially maintained.
- Straight rivers (sinuosity < 1.5) generally occur on flat slopes with small width/depth ratios and low velocities. Although a river may have a relatively straight alignment the thalweg usually has a distinct meandering pattern.
- On steeper slopes the river becomes meandering (sinuosity > 1.5) and the width/depth ratio increases, as does the velocity.
- On even steeper slopes the sinuosity generally decreases and the river becomes braided, in conjunction with an even higher width/depth ratio.

Several researchers have identified thresholds between different channel patterns, but they differ somewhat from one study to another, which is a result of the different data sets being used as well as the difference in the definitions of the various channel patterns.

The discharge-slope relation developed by Leopold and Wolman (1957) separates meandering and steeper braided streams:

$$S = 0.0125Q^{-0.44} \qquad (4.4\text{-}1)$$

where Q is the bankfull discharge in m^3/s.

The following meandering-braided threshold has been developed by Begin (cited in Carson, 1984):

$$S = 0.0016Q^{-0.33} \qquad (4.4\text{-}2)$$

Carson (1984) pointed out the importance of including the sediment particle size in the relationship, since streams with gravel beds must plot higher on a Q-S diagram than sand bed rivers, simply because it requires more power to transport gravel than sand. Henderson (cited in Chang, 1988) obtained the following equation for gravel-bed rivers:

$$S = 0.0002{d_{50}}^{1.15}Q^{-0.46} \qquad (4.4\text{-}3)$$

Chang (1979) developed channel pattern thresholds, based on the minimisation of stream power theory. Unlike other researchers, however, he argued that there can be a transition from straight to braided, before a river becomes meandering. With an increase in valley slope, however, the river tends to become less sinuous and more braided again, as indicated in Figure 4.4-1.

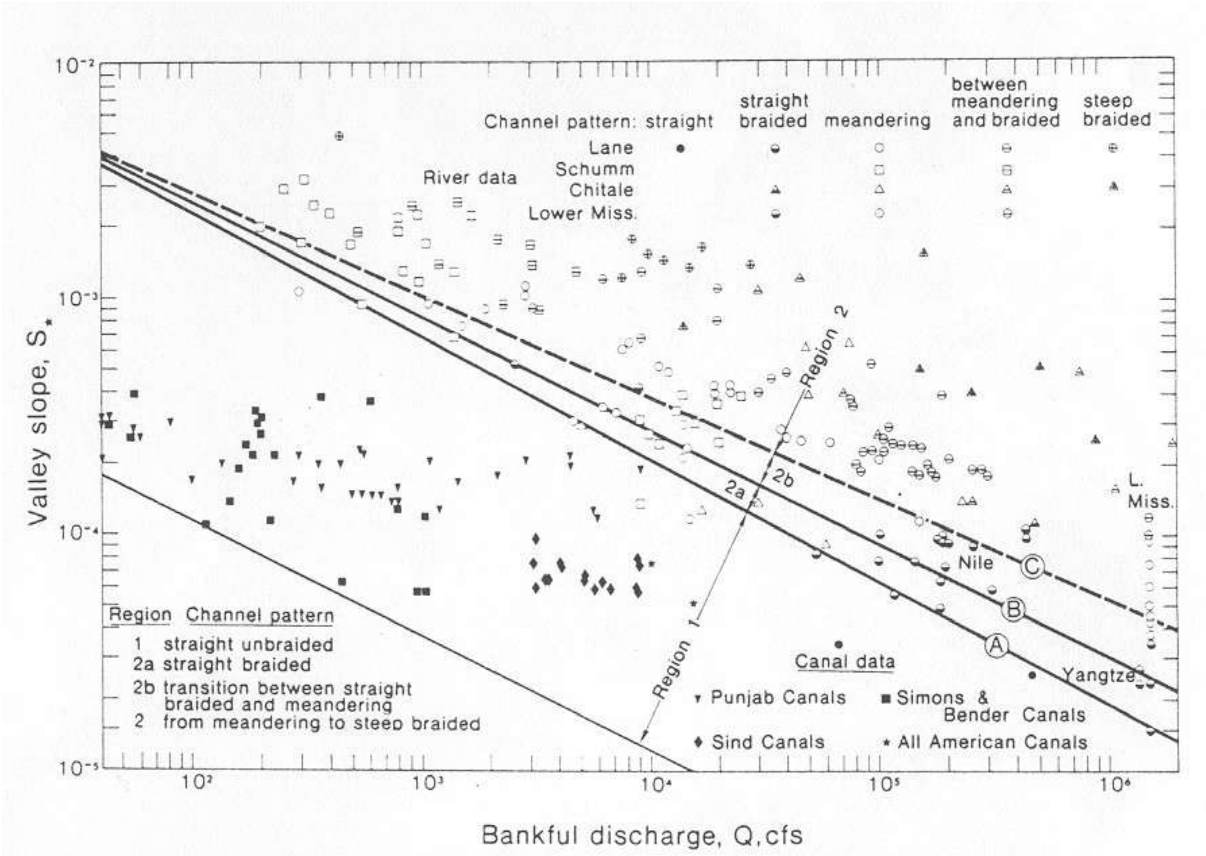


Figure 4.4-1 Channel patterns of sand streams (Chang, 1979)

A small change in channel slope can result in a major change in channel pattern, and it is therefore useful to establish a discharge-slope relationship also applicable to semi-arid and arid rivers.

Meandering river is defined as having a sinuosity of greater than 1.5 and braided rivers generally occur on slopes steeper than those of meandering rivers. The position of the threshold separating meandering and braided rivers would therefore be expected to be found in the upper region of Figure 4.4-2 where the sinuosities start decreasing. A threshold was observed, based on a trend of increasing sinuosities in the lower part of the graph, followed by a decrease in sinuosities in the upper part. The data in Figure 4.4-2 indicate that braided rivers are separated from meandering channels by a line described by the following equation:

$$S = 0.159 Q_{10}^{-0.557} \qquad (4.4\text{-}4)$$

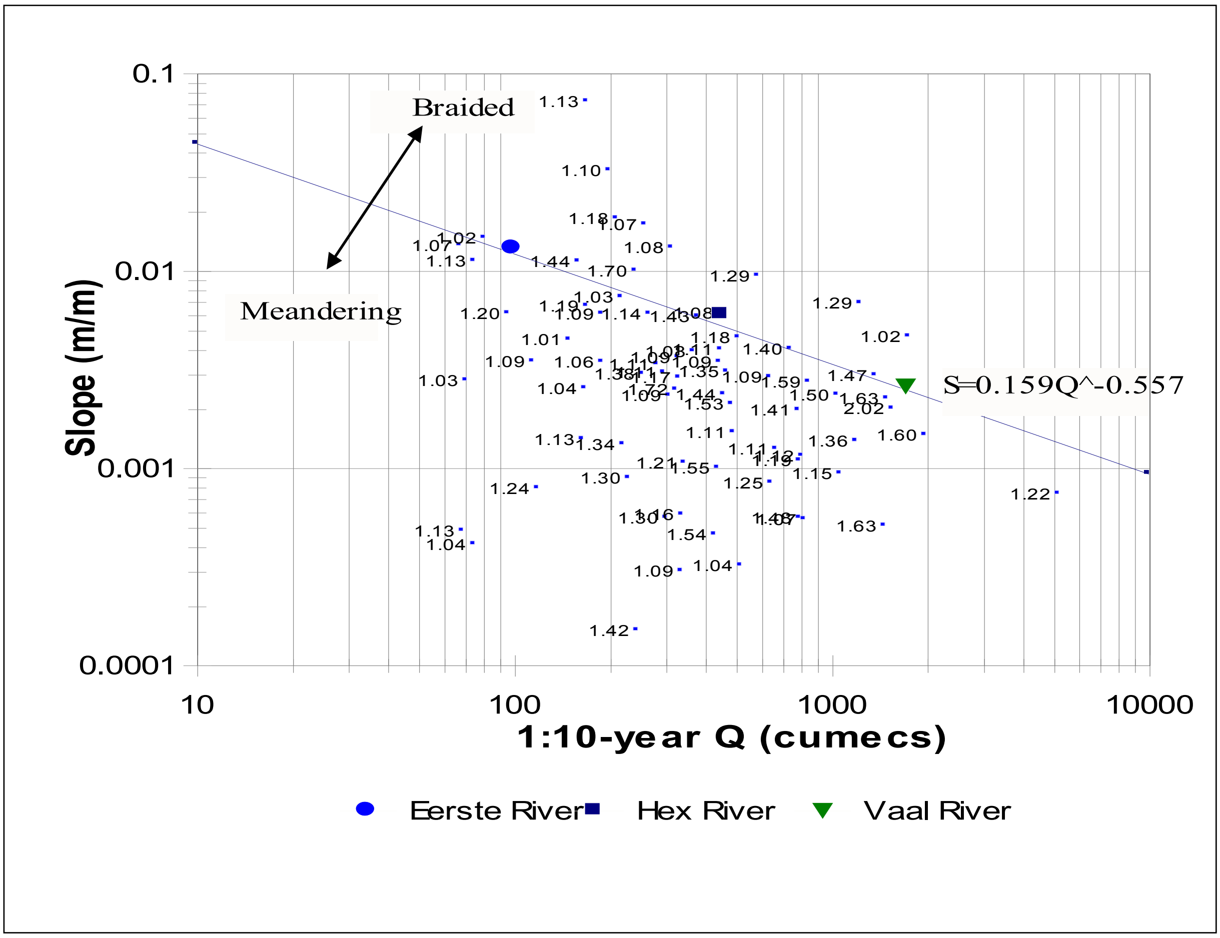


Figure 4.4-2 Threshold line separating meandering and braided rivers (sinuosity indicated)

4.5 Applications

In this section the applicability of the methods developed in the previous sections is tested using the Pongola River, downstream of Pongolapoort Dam South Africa, as an example.

The 1:10-year flood changed from 1877 m^3/s to 759 m^3/s after dam construction and the median particle size changed from 0.19 mm to 1 mm. The channel geometry of the natural river, the impacted river and the predicted values for both are summarised in **Table 4.5-1**. The ranges for the observed data given in the table indicate the natural variability of both the width and depth.

Table 4.5-1 River channel geometry of the Pongola River

	Natural (Pre-dam)		
	Observed	Calculated (eq.	Calculated (eq.
Average width	148 m	176 m	207 m
Range (width)	83 - 343 m	-	-
Average depth	4.6 m	3.8 m	6.0 m
Range (depth)	3.7 - 5.5 m	-	-
Slope	0.0015	-	-
	Post- Dam		
	Observed	Calculated (eq.	Calculated (eq.
Average width	60 m	139 m	129 m
Range (width)	39 - 135 m	-	-
Average depth	4.7 m	2.7 m	4.9 m
Range (depth)	-	-	-
Slope	0.0015	-	-

From Table 4.5-1 it can be seen that the average predicted values for the natural river differ only by about 17% for the regime equations developed during this project, whereas the predicted widths for the altered river differ considerably. The rather small widths observed from aerial photos 23 years after the dam was built could be a result of an almost constant release of 5 m^3/s from the dam in recent years. The constant releases could have created favourable conditions for vegetation, which could have encroached onto the river channel thereby reducing the channel width. The Domoina flood of 1984 with a peak inflow of 13000 m^3/s, was almost completely absorbed by the dam, which was almost empty when the flood reached the dam. This means that the river reach below the dam has not experienced any large floods since the dam was built, which could also have contributed to the fact that the river channel has narrowed to such a degree.

Evidently the methods available for predicting stable channel geometries are not very precise because they do not take into consideration all the factors that determine the channel geometry. Considering however that it is almost impossible to account for all these factors and often very little information is available, the methods outlined in this chapter are still very valuable for natural rivers. In the case of a river affected by a dam these regime equations may be useful if the releases/spills from the dam do not differ drastically from the natural flow pattern. The regime equations are however not applicable to rivers where the flow pattern has changed drastically. In order to determine the morphological changes a river undergoes when affected by a dam, more detailed analyses are necessary.

4.6 Alternative Width Equations for significantly altered floods

Since it seems that the use of a 1:10-year flood peak, or any other flood peak calculated by means of conventional statistical methods, for predicting the resulting channel geometry is unreliable, a different approach will have to be used. More reliable results could be obtained by using basic discharges such as the mean daily flow. Williams and Wolman (1984) have done a study of the impacts of dams on a large number of North American rivers. They have found that the average width downstream of a dam can best be described as follows:

$$B_2 = 13 + 0.5Q_m + 0.1Q_p \tag{4.6-1}$$

where B_2 = average bankfull width after dam construction (m)

Q_m = arithmetic average of annual mean daily flows since dam construction (m^3/s)

Q_p = average of annual 1-day highest average flows before dam construction (m^3/s)

A similar type of equation was sought with semi-arid (South African) river data. The following data were collected for 12 rivers on which dams had been built:

- Pre- and post-dam widths (B_1/B_2) in m
- Pre- and post-dam mean annual runoff (MAR_1/MAR_2) in m^3/s
- Pre- and post-dam mean annual maximum flood peaks (Q_{a1}/Q_{a2}) in m^3/s
- Highest flood peaks for the pre- and post-dam periods (Q_{p1}/Q_{p2}) in m^3/s
- Mean annual average daily flow (Q_{ad1}/Q_{ad2}) in m^3/s

It was of course found that the width before dam construction had the biggest effect on the width after dam construction, as well as the mean annual runoff. To a somewhat lesser degree the mean annual maximum flood and the highest flood peak also play a role. The mean annual maximum flood is significant due to its frequency, while the highest flood peak is important because of its magnitude, although it is not clear which of these two discharges is more important. Therefore the following two equations are presented, which yield very similar results, with practically the same accuracies:

$$B_2 = -3.40 + 0.856 \cdot B_1 + 0.142 \cdot MAR_2 - 0.0013 \cdot Q_{p1} \tag{4.6-2}$$

$$B_2 = -1.02 + 0.805 \cdot B_1 + 0.183 \cdot MAR_2 - 0.00036 \cdot Q_{a1} \tag{4.6-3}$$

The r^2 values are in both cases 0.99, with the accuracy ranges shown in **Table 4.6-1** and the observed (aerial photographs) and predicted widths shown in **Table 4.6.2**.

Table 4.6-1 Accuracy ranges for alternative width equations

Equation	$0.67 < \frac{B_{calculated}}{B_{observed}} < 1.5$	$0.5 < \frac{B_{calculated}}{B_{observed}} < 2$	$0.33 < \frac{B_{calculated}}{B_{observed}} < 3$
4.6-2	100 %	100 %	100 %
4.6-3	100 %	100 %	100 %

Table 4.6-2 Post-dam observed and predicted widths

Dam	River	Observed width (m)	Predicted width (m) Eq. 4.6-2	Predicted width (m) Eq. 4.6-3
Albertfalls	Mgeni	27.6	24.8	26.0
Gamkapoort	Gamka	55	53.8	52.9
Gariep	Orange	255	255.9	255.3
Krugersdrift	Modder	24	22.9	24.3
Roodeplaat	Pienaars	60	59.0	54.5
Spioenkop	Thukela	36.3	43.2	43.8
Theewaterskloof	Sonderend	33	29.0	29.7
Pongolapoort	Pongola	60	59.0	62.0
(Vioolsdrif)	Orange	208	206.2	206.9

4.7 Summary

This chapter was mainly concerned with the evaluation of regime equations for rivers. The concept of a dominant discharge was discussed and while many researchers equate the bankfull discharge with the dominant discharge, it seems that in semi-arid conditions the dominant discharge will be more in line with the 1:10-year flood peak. Existing international regime equations were studied and new regime equations were calibrated with South African river data and verified against international river data. The new equations (**3.3.17** and **3.3.18**) compare favourably with international regime equations. However, these new regime equations were found to be unsuitable for rivers that are highly impacted by dams, and alternative width equations (**3.7.2** and **3.7.3**) were developed for these rivers.

With these regime equations it is possible to predict the equilibrium (stable) river width and depth. However, they do not take into considerations any temporal or spatial changes. In order to determine the sediment balance in the river, the variations in discharge and channel geometry, which influence the sediment transport, have to be known, as well as the sediment transport processes that drive these changes.

5. Impacts of dams on the ecosystem related to fluvial morphological changes

5.1 Introduction

There is growing concern worldwide regarding the increasing rate of deterioration of the natural environments of rivers. The over-exploitation of river flow and manipulation of flow regimes, most obviously as a result of in-channel dams, has been widely documented as a major factor affecting the condition of rivers (McCully 1996), with an emerging recognition of the broader environmental and social costs associated with the loss of goods and services provided by riverine environments (WCD 2000).

Some countries have now initiated activities to mitigate against the damage caused by modified flow regimes on rivers and their associated ecosystems (Tharme 2003). These activities have precipitated a massive call on river scientists to become involved in the development of tools to assist in a new approach to water resource management, thus spawning the relatively new science of environmental flow (EF) assessments. EF assessments are generally aimed at providing management recommendations on the nature of modified flow regimes for rivers that are to be exploited for their water resource. Water that is left in an aquatic ecosystem, or released into it, to maintain it at a specified level of condition (health), is often termed an environmental (or instream) flow or environmental water requirement (EWR). Although EF assessments are usually made when new developments are planned, they can also be performed to assist in the restoration of desirable attributes in rivers that have deteriorated through manipulation of their flow regimes.

5.2 How river ecosystems function

Rivers are defined by the interaction of climate, geology and geomorphology, that determine the suite of physical and chemical conditions along their lengths and over time, and which in turn gives rise to the diversity and characteristics of the life that inhabits them. Climate and geology define the availability of sediments within the catchment, the nature of riparian vegetation and hence the major energy source (instream primary production in open-canopied streams versus decaying organic matter contributed from the riparian zone) that underpins riverine food chains. The physical forces associated with flowing water at once control the erosion and redistribution of channel materials and define the nature of instream physical conditions and spatial heterogeneity, for example the nature of morphological units such as lateral bars, plane bed or pool – riffle features, which in turn are important determinants of other factors such as stream retentiveness and the diversity of physical micro-habitats. Variability in flow is the major regulator of the availability, spatial arrangement and condition of instream and floodplain aquatic habitats, and provided for the continued integration of different components of the riverine ecosystem. Biological communities in rivers, therefore, are the result of a complex interplay of these drivers, and their own interactions in the form of feeding, reproduction, predation, competition, disease and so on. Figure 5.2-1 summarises the important factors that determine riverine species assemblages.

5.3 General effects of water resource development on ecosystem condition

One of the most obvious benefits provided by the rivers within any catchment is the water that can be stored, to be abstracted for human industry, or manipulated in releases to provide energy. These are, however, only some of the *goods* that natural river ecosystems may provide. Others less obvious might be river, estuarine and marine fisheries; extensive floodplains that support wildlife; or the food, fuel, craft and medicinal plants provided by riparian vegetation. The *services* provided by natural river ecosystems might include good bank stability brought about by a complex community of riparian trees, and thus low sediment loads in the river; waste assimilation; recreation; aesthetics; tourism; religious and cultural activities.

Manipulation of the flow regime reduces the ecosystem's ability to provide other goods and services. The loss of these goods and services is a cost that needs to be weighed against the benefits that accrue from the use of water in development of the land for agriculture, for industry and for social upliftment.

At different levels of water resource development and economic activity, the alteration of the original goods and services may be more or less pronounced. In the early stages of development, the goods and services that depend on the natural flow regime (e.g. the fisheries or floodplains; the recreational value; natural biodiversity) might decline (costs), but the water resource development, perhaps a dam, that caused this, will have led to increased food or energy production or allowed people to have running water in their homes (benefits). With increasing water exploitation, flow in the river might reduce to the point where the flow-dependent goods and services, such as fisheries, riparian plants etc., are destroyed. Furthermore, the loss of some of the services provided by a river may incur additional and unforeseen economic costs. For example the loss of assimilative capacity (through reduced dilution) might result in previously "acceptable" pollution loads becoming health hazards for local communities or requiring expensive water purification treatment for supply schemes; loss of riparian integrity may result in establishment and encroachment of alien vegetation with concomitant impacts on flood damage and water yield (*sensu* Ractliffe *et al.* 2003).

Too often in the past, riverine ecosystems have been viewed simply in terms of the water that they can supply, and management decisions have thus favoured those who stand to gain from using this benefit directly, often at the unforeseen or unexamined expense of those who depend on the other ecosystem goods and services (McCully 1996).

Deciding on what particular goods and services are going to be enjoyed, and what costs are deemed acceptable, is a political decision, i.e. a trade-off that may benefit one social grouping at the expense of another, but also an ecological decision, as it will determine the condition in which the resource (the river ecosystem) will be maintained into the future.

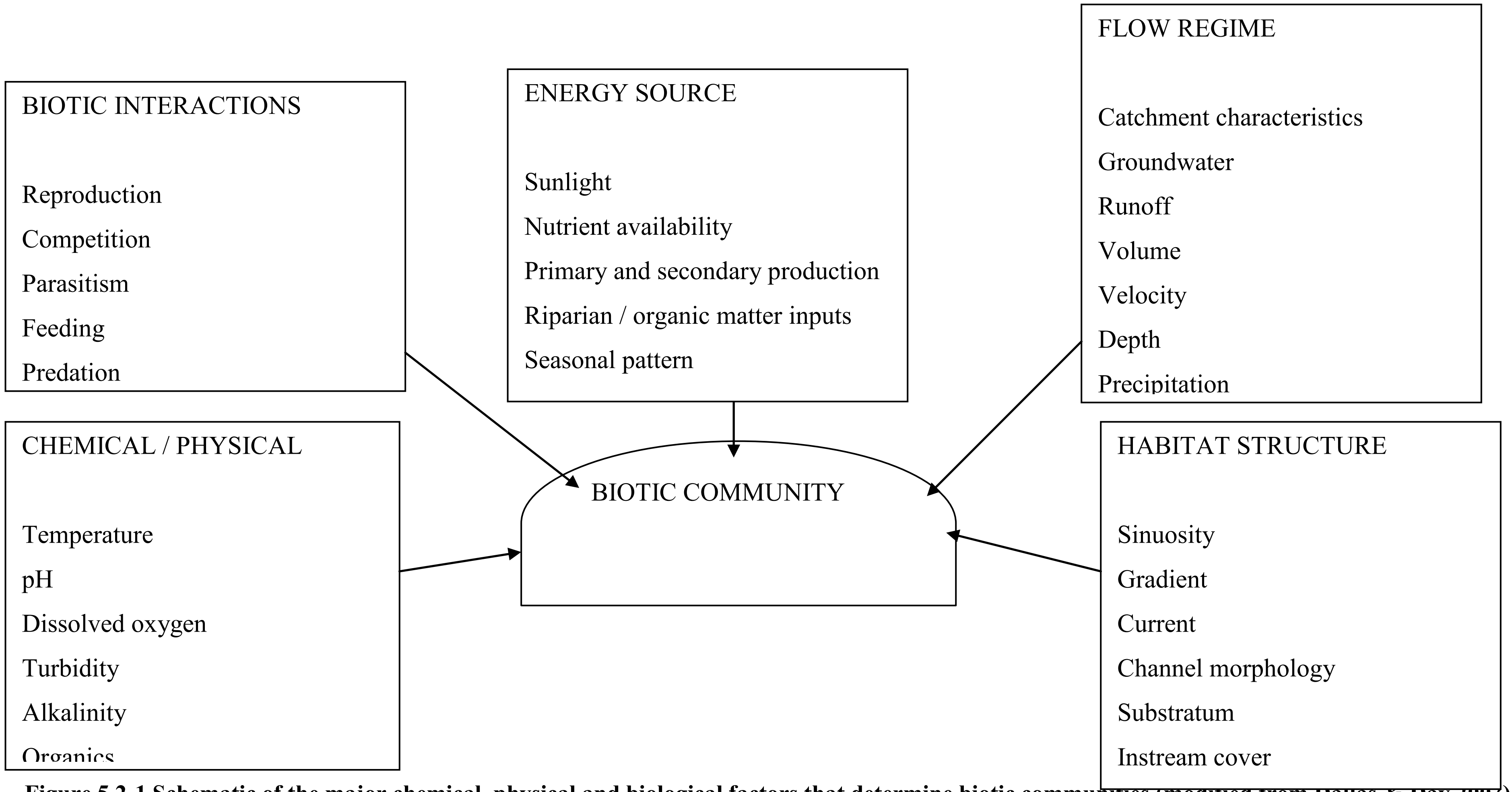


Figure 5.2-1 Schematic of the major chemical, physical and biological factors that determine biotic communities (modified from Dallas & Day 2003).

5.4 The parts of a river ecosystem

All parts of a river ecosystem are inter-connected. Disturbance to one part will create a greater or lesser response over much of the system. For instance, a large in-channel dam can stop migration of fish to spawning grounds in the headwaters, impact a marine fishery at the other end of the system, and eradicate the floods needed to maintain floodplain vegetation in the middle reaches that is used for subsistence. Clearing bank vegetation can lead to bank collapse, increased sediment loads in the river, clogged fish gills and blanketing of spawning grounds, as well as reduced life of downstream reservoirs. Management of rivers and their flows should thus involve consideration of all likely responses of the river to a planned disturbance.

5.5 The parts of a flow regime

The flow regime is the pattern and timing of high and low flows in a river. Each river's flow regime is different, depending on the characteristics of its catchment and the local climate, although regional trends do emerge. River ecologists recognise that different parts of the flow regime play different roles in maintaining a river (Table 5.5-1) (King, 2002).

Table 5.5-1. Different kinds of river flow, and their importance for a healthy river (King, 2002).

Flow component	Importance
Low flows	The low flows are the daily flows that occur outside of high-flow peaks. They define the basic seasonality of the river: its dry and wet seasons, and degree of perenniality. The different magnitudes of low-flow in the dry and wet seasons create more or less wetted habitat and different hydraulic and water-quality conditions, which directly influence the balance of species at any time of the year.
Small floods	Small floods are usually of great ecological importance in semi-arid areas in the dry season. They stimulate spawning in fish, flush out poor-quality water, mobilise smaller sediments and contribute to flow variability. They re-set a wide spectrum of conditions in the river, triggering and synchronising activities as varied as upstream migrations of fish and germination of riparian seedlings.
Large floods	Large floods trigger many of the same responses as do the small ones, but additionally provide scouring flows that influence the form of the channel. They mobilise coarse sediments, and deposit silt, nutrients, eggs and seeds on floodplains. They inundate backwaters and secondary channels, and trigger bursts of growth in many species. They re-charge soil moisture levels in the banks, inundate floodplains, and scour estuaries thereby maintaining links with the sea.
Flow variability	Fluctuating discharges constantly change conditions through each day and season, creating mosaics of areas inundated and exposed for different lengths of time. The resulting physical heterogeneity determines the local distribution of species: higher physical diversity enhances biodiversity.

Manipulations of the flow regime will affect the river ecosystem, and we have the choice of ignoring this in water-resource developments and awaiting (or being surprised by) unwelcome changes as the river responds, or trying to predict the potential changes and managing them. Until about fifteen years ago most, if not all, countries were doing the former. The following section describes how this has led to dams changing rivers.

5.6 The impacts of dams on river ecosystems

Dams are designed to manipulate the flows of rivers. In doing so, they impact indirectly on the downstream river ecosystem by potentially affecting every part of the flow, sediment, thermal and water-quality regimes. They may also impact the ecosystem directly by, for instance, blocking fish passage. Each of these aspects is discussed briefly below.

5.6.1 Low flows

Dams may store low flows during the wet season, for release downstream in the dry season. In doing so, the seasonal pattern of low flows may be partially or wholly reversed, eradicating conditions needed for life cycles to reach completion. Aquatic plants that need to push flowers above the water surface in the dry season for pollination, may be unable to and so gradually species disappear. Aquatic insects that are programmed to emerge during months when flow is usually quiet, to fly, mate and lay eggs in the river, may be forced to emerge in fast turbulent water, and so die. If they can adapt to emerge in months when flows are slower, they may meet unsuitable air temperatures or find no food, and so still die.

In some rivers, dry-season low flows are periodically completely eradicated by damming or direct abstraction. Such reaches will lose their fish, and other river life will be drastically reduced in diversity and numbers because most cannot cope with periods of drying out, even for a few hours. In ephemeral rivers, dams or other abstractions may halt the movement of groundwater along the channel, killing ancient riparian trees. This has happened in the Luvhuvhu River, Kruger National Park (which should be a perennial river), and could happen to the linear oases of trees along the rivers flowing east to west across Namibia that support the large desert mammals and local indigenous peoples (King, 2002).

The ecosystem components do not exist in isolation, but are interdependent. Insects provide food for fish; leaves falling from native trees provide the right food at the right time for the insects; plants stabilise banks, controlling sediment inputs into rivers, and so protecting spawning and feeding grounds, gills and eggs. As flow impacts any of these components, the effects are felt throughout.

5.6.2 Intra-annual floods

Small and medium floods may be completely stored in reservoirs. These floods are thought or known to: sort riverbed sediments, maintaining physical (and therefore biological) diversity move sediments along the river, maintaining bars and riffles (low flows cannot do this, and very high flows may bring more sediments into the river than they remove) help maintain and control the spread of marginal vegetation such as reed beds, trigger fish spawning provide depth of water for fish migrations along the river, enhance water quality during the dry months.

Sometimes such floods spill over the dam wall once the reservoir is full. This may not happen until late in the wet season, and so be of limited use for ecosystem maintenance. Fish triggered by spills to spawn late in the season, for instance, will produce juveniles that may not be sufficiently developed to survive the coming adverse season. This can happen naturally, but when it is managed to happen year after year, the fish species so affected will decline and could disappear. Small and medium floods could be released from the dam to encourage early spawning, but with recognition that any reduction in the numbers of floods (e.g. used to be 15 per year, now two per year released from the dam) translates into a higher risk of the fish numbers declining. This is because the fish have fewer chances to spawn, and there are fewer batches of young to survive sporadic adverse conditions such as cold spells, toxic spills or bulldozing of the riverbed.

5.6.3 Inter-annual floods

The large floods that occur less often than yearly are thought or known to:
maintain riparian belts of trees that can be metres to hundreds of metres wide on either bank;
scour channels, maintaining their capacity to carry flood water;
scour riverbeds, cleansing substrates and flushing fines that clog spawning and feeding grounds;
eradicate patches of in-channel and bank vegetation, enhancing diversity as new growth appears.

One major importance of larger floods is through the geomorphological changes they bring, which may not be directly 'welcomed' by the aquatic plants and animals. Fish, for instance, have to seek refuge from them. They are essential as re-setting agents for the river, however, scouring slimy films from rocks, renewing habitats and eradicating old and diseased individuals. Other important functions of large floods are their flooding of floodplains and scouring of estuaries including maintaining an open mouth. Both of these are areas of high productivity and diversity, highly important to people and wildlife.

It is often claimed that dams cannot harness the larger floods, which will spill over. They may well reduce their size, however, so that ones of a magnitude that occurred on average every two years could occur as a spill of that magnitude only once in five to ten years. Some consequences of floods becoming rarer can be inferred from earlier sections of this paper.

5.7 The Ecological Reserve

The "Ecological Reserve" is the mechanism adopted by same countries, such as South African, for managing water resources sustainably. The term "Ecological Reserve" is defined as "that quantity and quality of water required to protect aquatic ecosystems in order to secure ecologically sustainable development and use of the … water resource" (DWAF 1998).

In adopting the Reserve as the mechanism for management, there is the implicit recognition that water is not differentiable from the ecosystems that may be exploited for water supply, i.e. that the resource, the ecosystem, needs to be maintained in a sustainable condition in order to supply water and other ecosystem goods and services. The Ecological Reserve for a river is, in effect, the Environmental Water Requirement (EWR) finally adopted, once trade-offs regarding different costs and benefits have been made. The Ecological Reserve for any given river should ideally thus explicitly indicate which goods and services are prioritised within the catchment, and is linked to the achievement of a particular state of the ecosystem, depending on what state of the resource will benefit stakeholders most.

5.8 Environmental Flow assessment methods

Four main types of approaches to EF assessments have developed over the past three decades, namely hydrological, hydraulic rating, habitat simulation and holistic methods. The reader is referred to Tharme (2003) for a full review and bibliography. King *et al.* (1999), provide guidelines for the different circumstances in which each of these kinds of EF assessment would be more applicable, summarised in Table 5.8-1.

5.8.1 Hydrological methods

Hydrological methods were the earliest methods developed, typically as rapid, desktop approaches to advising on mitigatory flows for managed rivers. They use one or more summary statistics gleaned from hydrological data sets, usually a percentile from the annual flow duration curve, to set what is often called a minimum flow for the river. Usually the set flow is assumed rather than known to have ecological relevance. A major drawback with these approaches is that they do not take into account any features of the river other than its (usually monthly) flow data. The results are broad-brush guides to flows for ecological maintenance that are insensitive to the nature of individual rivers.

5.8.2 Hydrological rating methods

These sorts of methods require the field measurement of hydraulic variables such as wetted perimeter, wetted width or depth measured at one or more cross-sections at representative sites along the river over a range of flows. These values are plotted against discharge, and thresholds sought where there is a change in the slope of the curve. The implicit assumption is that when flow falls below such a threshold, there will be a sharp change in the quality of habitat and thus repercussions for the aquatic life and ecological integrity of the ecosystem. The generic Wetted Perimeter Method is the most widely applied of these approaches (Gippel & Stewardson 1998). Whilst these approaches, using physical variables as a surrogate for ecological attributes, provide some river-specific information and insights on ecosystem functioning, the assumption of ecological significance associated with the thresholds of change in hydraulic variables is not tested.

5.8.3 Habitat-simulation methodologies

More complex habitat-rating approaches evolved from the hydraulic-rating methods in the late 1970s and 1980s, and link discharge-dependent hydraulic characteristics of river habitats with extensive data on the habitat requirements of aquatic plants and animals in the same river, for example, the Instream Flow Incremental Methodology (Stalnaker *et al.* 1995). Hydraulic data collected at many cross-sections are used to compile a description of representative river sites in terms of the hydraulic habitat they provide over a range of flows. The descriptions are linked to known hydraulic-habitat requirements of selected plant or animal species, to provide an output, usually in the form of graphs, of how much habitat is provided for that species at any discharge (see section 6). These relationships can be used to identify what are perceived to be optimal flows for the species selected. Advantages of these approaches are their strong ecological links and quantitative outputs that can be used in water negotiations. Drawbacks include their complexity; their focus only on habitat, often without recognition of the wider environmental needs of species; their focus on aquatic species to the detriment of riparian species; and their focus on lower flows to the detriment of floods (King & Tharme 1994).

5.8.4 Holistic approaches

Holistic methods represent the most recent approaches to EF assessment, and have been pioneered in South Africa and Australia (Tharme 2003). They address all parts of the river ecosystem and all parts of the flow regime. Their strength is that they can incorporate diverse information on the links between flows and ecosystem components or ecosystem goods and services, for instance, socio-economic and resource economic data can be used to predict the implications for subsistence users of river resources, of changing river flows. Holistic approaches are essentially structured data and information management tools that require and use hydrological, hydraulic, sedimentological, geomorphological, chemical, thermal, botanical (aquatic, marginal and riparian plants), zoological (fish, invertebrates, algae, water birds, other wildlife), and social data to compile an understanding of the river and develop a consensus prediction of how it would change with flow changes. Their advantages are immense because of their wide scope, because they contribute toward national databases that enhance understanding of the rivers, and because ultimately they allow derivation of their own rapid versions based on past applications. Their main drawback is the cost of large multi-disciplinary teams optimally working over at least one annual hydrological cycle to gather river specific data.

In South Africa, the Building Block Methodology (BBM) has been the routine approach to EWR assessments, developed by a number of river scientists with the support of Department of Water Affairs and Forestry (DWAF) (King & Louw 1998), and for which a manual has been written (King *et* *al*. 2000). In this method, river scientists working in an interdisciplinary manner compile a flow regime "from scratch" by motivating for blocks of flow within different categories, such as wet season low flows, dry season low flows, different category floods etc. (Figure 5.8.4-1). Hydraulic measurements are important to link different magnitude discharges to physical properties of the river at representative sites used for the assessment, for example the river stage reached by the 1:2 year flood and thus extent of riparian inundation, or the velocity range associated with a range of low flow discharge values. Each "building block" flow motivation requires an ecological motivation to be advanced by one or more river specialist. An example of this might be something like "a flow of 0.06 $m^3 s^{-1}$ will maintain riffle depths above 10 cm and velocities above 0.2 $m s^{-1}$ (derived from hydraulic modeling), which are essential to provide wetted habitat for riverine invertebrates and / or prevent competitive exclusion of species x by species y".

Table 5.8-1. Comparison of the four main kinds of environmental flow methodologies (after King *et al.* 1999).

Type	Ecosystem components addressed	Data needs	Expertise	Complexity	Resource intensity (time, cost, technical capacity)	Resolution of output (the EF)	Flexi-bility	Appropriate level of application
Hydrological	Non-specific	Low (primarily desktop): measured or simulated hydrological record	Manipulate hydrological date	Low	Low	Low	Low	Reconnaisance level planning
Hydraulic-rating	General aquatic habitat	Low-medium (desktop and limited field): measured or simulated hydrological record; one or a few hydraulic variables from a cross-section	Manipulate hydrological data; perhaps some hydraulic modelling	Low-medium	Low-medium	Low	Low	Low-conflict water-resource allocations
Habitat-simulation	Aquatic habitat for selected species	Medium-high (desktop and field): measured or simulated hydrological record; many hydraulic variables at many cross-sections; habitat data for selected species	Advanced hydrological and hydraulic modelling; specialist ecological expertise on habitat requirements of selected species	Medium-high	High	Medium-high	Medium	Water allocations for high conservation areas where in-channel habitat is main concern
Holistic	Whole aquatic and riparian ecosystem; can include groundwater, wetlands, floodplains, estuary, delta, and subsistence users	Medium-high (desktop and field): measured or simulated hydrological record; many hydraulic variables at many cross-sections; biological data on flow-related habitat requirements of wide range of species	High - advanced hydrological, hydraulic, and habitat modelling; chemical and thermal modelling if possible; specialist expertise on all ecosystem components; social and economic expertise as required	Medium-high	High	High	High	Developed and developing countries; Flow management in any size river, including ones of high strategic or conservation importance; Also dam de-commissioning and river rehabilitation

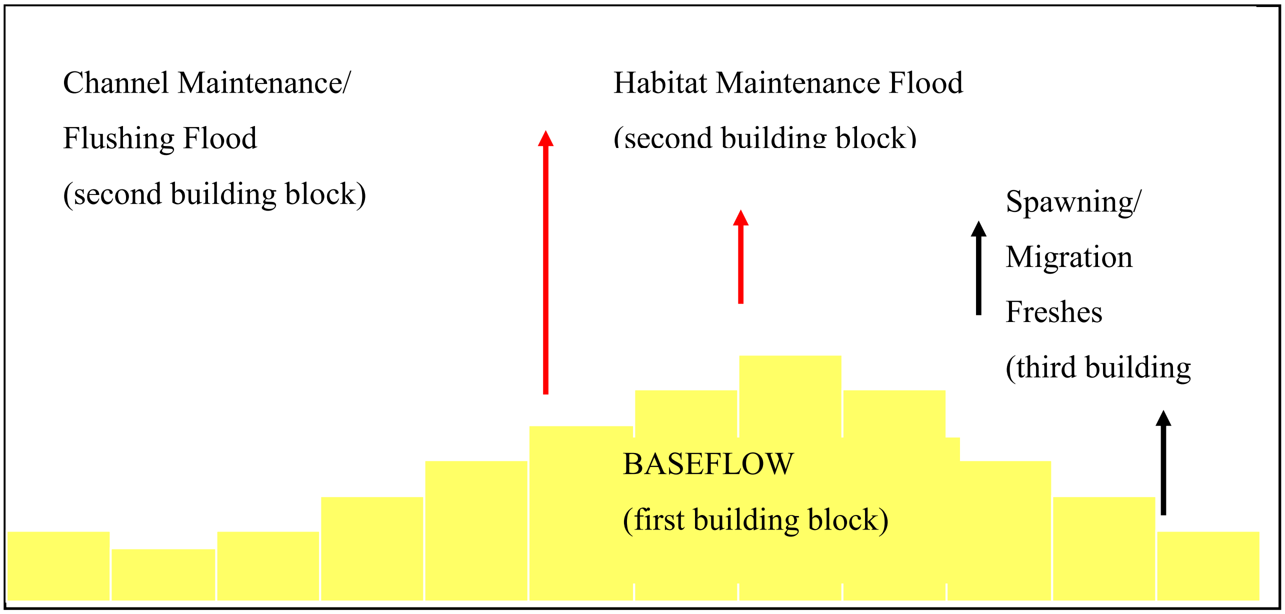


Figure 5.8-1 Schematic of the major "building blocks" of the BBM holistic EF methodology.

In the BBM, the ecological motivations need to be addressed to the pre-defined "future state" decided for the river in question – i.e. the trade-off on what particular goods and services are going to be enjoyed, and what costs are deemed acceptable (and thus the future conditions in which the river will be maintained) is established upfront.

The BBM was one of the first holistic methods to be developed. More recently, ecologists involved in EF assessments have taken the basic ideas in the BBM - i.e. flow-related ecological links and interdisciplinary assessment - and expanded on this to develop a data management system that allows for the ecological consequences of reducing discharges in the range of flow bands to be incorporated into a single database. This is the Downstream Response to Imposed Flow Transformations (DRIFT) process (King *et al.* 2003). DRIFT is revolutionary in that it is scenario-based, allowing for the comparative evaluation of the consequences of any number of different flow regimes, but where these consequences are derived from the ecological relationships (and social consequences for subsistence users, should such data be available) established between flows of different magnitudes and each ecosystem component.

5.9 EF assessments and science

Great strides have been made in developing methods for EF assessments over the past two decades, and the latest methods offer an enormous aid to the decision-making process for water managers. However, this approach to managing a country's natural water resources is heavily dependent on our ability to understand, and indeed, to quantify, the relationship between any one ecosystem component (providing a good or service) and the flow regime. Given the complexity associated with biotic communities, making this link between one or more aspects of the flow regime that can be easily quantified (such as from a flow duration curve) and a chemical or biological process or species requirement, requires the combined skills of biological knowledge and hydraulic modeling tools, from the very simple to the sophisticated. This essentially is the cornerstone, or the "science" behind EF assessment. Some examples of current work in quantifying biotic - abiotic linkages in relation to flow are discussed in the sections that follow.

5.9.1 Sediment regime and the ecosystem

Dams trap sediments passing down the river, as well as altering flows. Because of this, the channel may show signs of degradation (loss of sediments), or aggradation (accumulation of sediments), depending on whether the remaining floods can move the remaining incoming sediments. In both circumstances the ecosystem changes, because different plants and animals live on or in different kinds of substrates. Most trees, for instance, cannot survive on banks degraded down to bedrock, whilst increasing amounts of sand encourage growth of reed beds. The highest diversity of aquatic insects is on well-scoured cobbles, and this is the favoured feeding area of many valued fish species such as trout. A shift of the riverbed to sand will reduce both diversity and abundance of the food species, as most cannot survive in sand. Those that can live in sand cannot be seen by, and therefore fed on by, the fish.

In developing regions such as southern Africa, millions of people are subsistence users of rivers. They may be using river resources for food, medicines, nutritional supplements, firewood, construction materials, potable and washing water, crafts, and grazing for animals. Shifts in the river ecosystem directly affect these poorest of poor people, often deeply threatening their health, ability to work, and spiritual well-being. Until recently, it was assumed that the major impact of dams on rural people was through displacement of those living in the planned reservoir basin. It is now known that the number of people affected downstream of a dam by the changing health of the river can be orders of magnitude greater than the number directly displaced by the project (WCD, 2000).

In evaluating progress made in eco-hydraulic studies, however, it is important to recognise that, despite the expansion in research, ecosystems are extremely complex, and identifying the relationships between diverse assemblages of animals and plants, and their abiotic drivers, is not easy. The abiotic parameters which may be considered drivers for one ecosystem may, with only slight alteration, produce a completely different outcome in a second ecosystem. For example, reduced low flow velocity may reduce the supply of nutrients to algal mats, causing resource limitation and reduced growth rates (Biggs & Stokseth 1996). However, the effect on invertebrates that feed on these algae will vary depending on whether the ecosystem is nutrient poor or nutrient enriched, the extent of shading or light availability, temperature regime, turbidity etc. (e.g. Marks *et al.* 2000).

The most reliable statements of the ecological consequences of flow reduction require considerable understanding of the biotic and abiotic relationships that govern each river under consideration. This requires scientific investment of a magnitude that is seldom afforded to river scientists in developing countries, but it is a need that is ignored at our own peril.

In strengthening the practice of environmental flow allocations, the following are some priorities:

- More investment in science needs to be made to improve the confidence that surrounds the ecological scenarios associated with flow alteration. Research projects that deal with fundamental relationships are important in extending the "knowledge capital" available for application to the EF assessment process.
- Measuring the habitat of benthic-dwellers is not satisfactorily achieved through standard hydraulic techniques. More attention to this area is require if the flow requirements of organisms at the very base of river food chains are to be adequately addressed, and this is an important area for collaborative study.
- Monitoring programmes should provide an avenue to make up for deficiencies in knowledge used in establishing the EWRs, and provision for this should be recognised in the resources allocated to monitoring programmes.

5.10 Case Study: Cahora Bassa Dam

5.10.1 Background

The Zambezi River is the fourth largest floodplain river in Africa and the largest system flowing into the Indian Ocean. Rising in Angola it has a catchment area of 1 570 000 km2, drains the Southern borders of the DRC and traverses Botswana, Zambia, Zimbabwe, Tanzania, Malawi and Mozambique. The river comprises three segments: Upper (1 078 km) from its source to the Victoria Falls, Middle (853km) between the Victoria Falls and Cahora Bassa Gorge, and Lower (593 km) from Cahora Bassa to the sea. Figure 5-10-1 shows a map of the lower Zambezi.

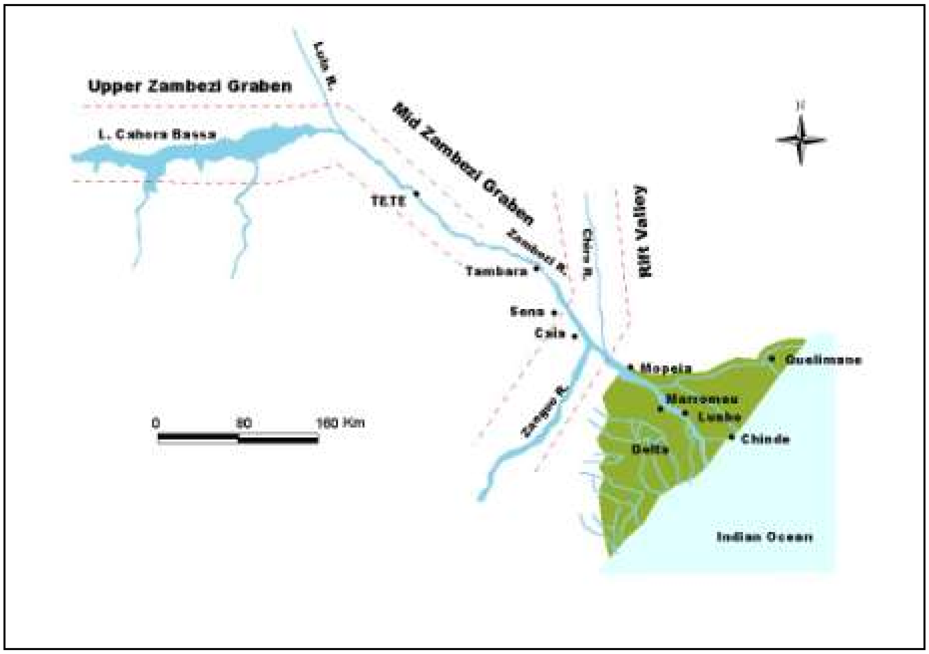


Figure 5.10-1 Schematic representation of the Lower Zambezi River

In the uplifted mountainous areas below Cahora Bassa, the channel is confined to a 500m wide narrow valley with relatively high gradients. Boulder and bedrock outcrops and high stream energies dominate the instream environment of the gorge zones. Downsteam of these zones the valley-floor-trough broadens to several kilometres. Because gradients are still relatively high and boundaries sediments are highly mobile, a braided sand-bed river dominates. The zone is further characterised by extremely high sediment fluxes.

Jackson (1986) describes the Zambezi as a 'sandbank' river with pronounced flood (Jan-April) and dry season (June-October) flows. The average floods ranges between 8 000 and 14 000 m_3/s. In this section we focus on the effects of the Cahora Bassa dam on the lower river.

Between December 1973 and October 1974 the Lower Zambezi was surveyed seven times at thirteen sites from the Zimbabwe border to the coast at Chinde in order to assess the potential effects of Cahora Bassa on the already regulated Lower Zambezi.

Recommendations that were made after the surveys included:

a) Reservoir filling over a minimum of 2 years.
b) Minimum compensation flow of 450 m_3/s during filling with releases to match seasonal cycles.
c) Filling from March 1975, to avoid loss of the flood.

Predictions about future ecological changes that would occur should the recommendations be ignored were also made:

a) A rapid decline in coastal fisheries and shrimp industry, and artisanal river Fisheries: the first two due to loss of silt and associated nutrients, the last to reduction of wetland flooding, loss of recruitment and exposure to main-channel predators.
b) Loss of mangroves and coastal erosion through flood reduction and silt loss (coastal erosion was evident during aerial surveys conducted on January 16, 1974; these were attributed to the effects of Kariba Dam (storage capacity 180 600 million m3) over 16 years).
c) Up to 70% reduction in sediment transport during floods, coupled to lack of scour and upstream penetration of the estuarine salt wedge.
d) Changes in riparian and wetland vegetation structure consistent with classically regulated rivers and concomitant decline of large mammal and bird populations on the Marromeu Wetlands.
e) Spread of human disease vectors due to increased habitat (pools, lack of flushing).
f) Invasion of wetlands by alien aquatic plants.

5.10.2 Flow curtailment in the lower Zambezi Valley

Lake Cahora Bassa with total storage capacity of 63 000 million m_3 commenced filling on December 5, 1974. It was rapidly filled in a single flood season (1974-1975) without compensation flows (60 m_3/s reached the river as leakage). By March 1975, an emergency flood release discharged 1.27 billion m_3 over 5 days to prevent overtopping the still incomplete wall. A discharge of 14 753 m_3/s was achieved with a combination of eight sluice gates and emergency spillways and inflows exceeded 20 000 m_3/s.

Figure 5.10-2 Shows a graph of recorded flood flows downstream of Cahora Bassa Dam.

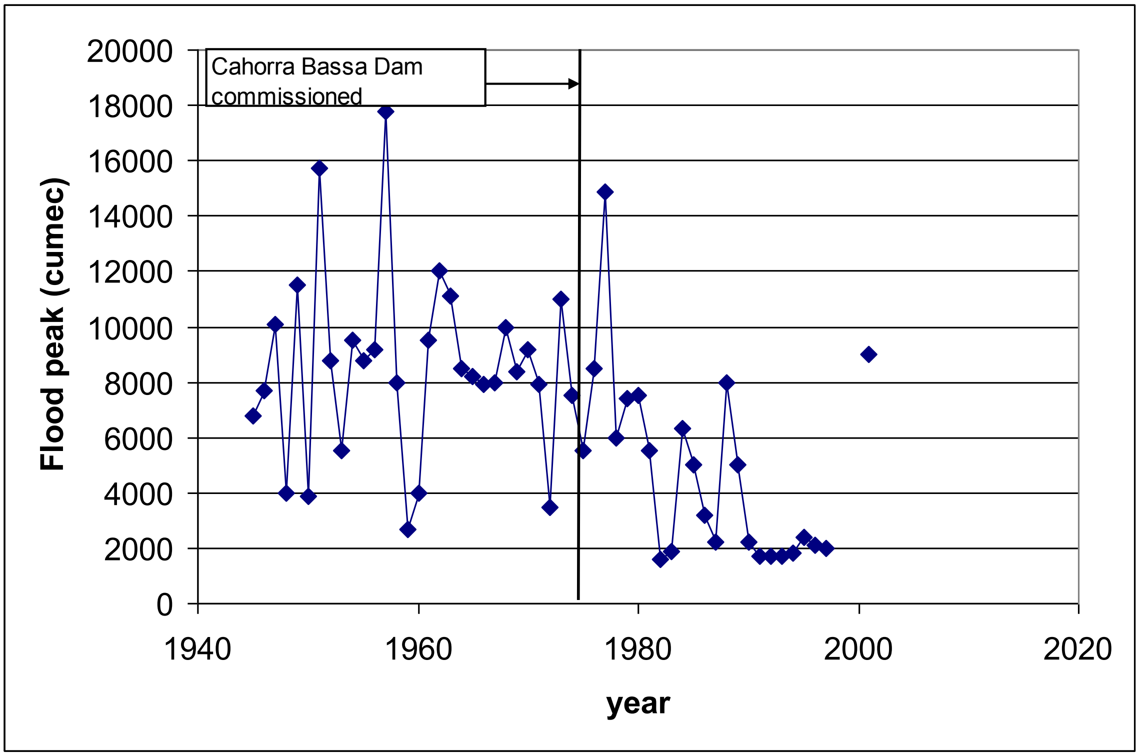


Figure 5.10-3 Observed historical flood peaks downstream of Cahora Bassa Dam site

The largest floods released from the dam occurred in 1978 at 14900 m_3/s, and in 2001 at 9000 m_3/s. After the 1978 flood new operating rules were adopted to attenuate the flood in Cahora Bassa as much as possible, and it was possible to attenuate the 1997 inflow into the reservoir of 12000 m_3/s, to an outflow of 2000 m_3/s. In 2001 the flood attenuation was however much less from an inflow peak of 13800 m_3/s to an outflow of 9000 m_3/s (35 % reduction). There have been no unregulated spills from the dam since its closure. Interestingly, owing to a variety of factors including Mocambique's 18-year-long civil war, the turbines have never produced full capacity and during June 1996, only 15 MW (installed capacity 2075 MW) were being produced while releases from the dam were constant at 758 m_3/s.

Aerial surveys, conducted during June 1996, indicated dramatic changes in the morphology of the river-floodplain system downstream of the dam. Morphological responses to flow regulation and the subsequent reductions in sediment loads and flows varied in the different river-floodplain zones. For example, due to enhanced flow capacities in the gorges, the majority of the river channel bars had eroded. The loss of these temporary sediment storage areas resulted in a 'canal' like system with marked reduction of in-channel habitat. In the anabranch zone, marked reductions in the magnitude and frequency of floodplain inundation have caused dominance of one main channel, whereas previously there were several active channels. Many secondary channels have become isolated from the main channel through silting of entrance points. Figure 3.3 shows a satellite image of the current (2000) river morphology 300 km downstream of the dam.

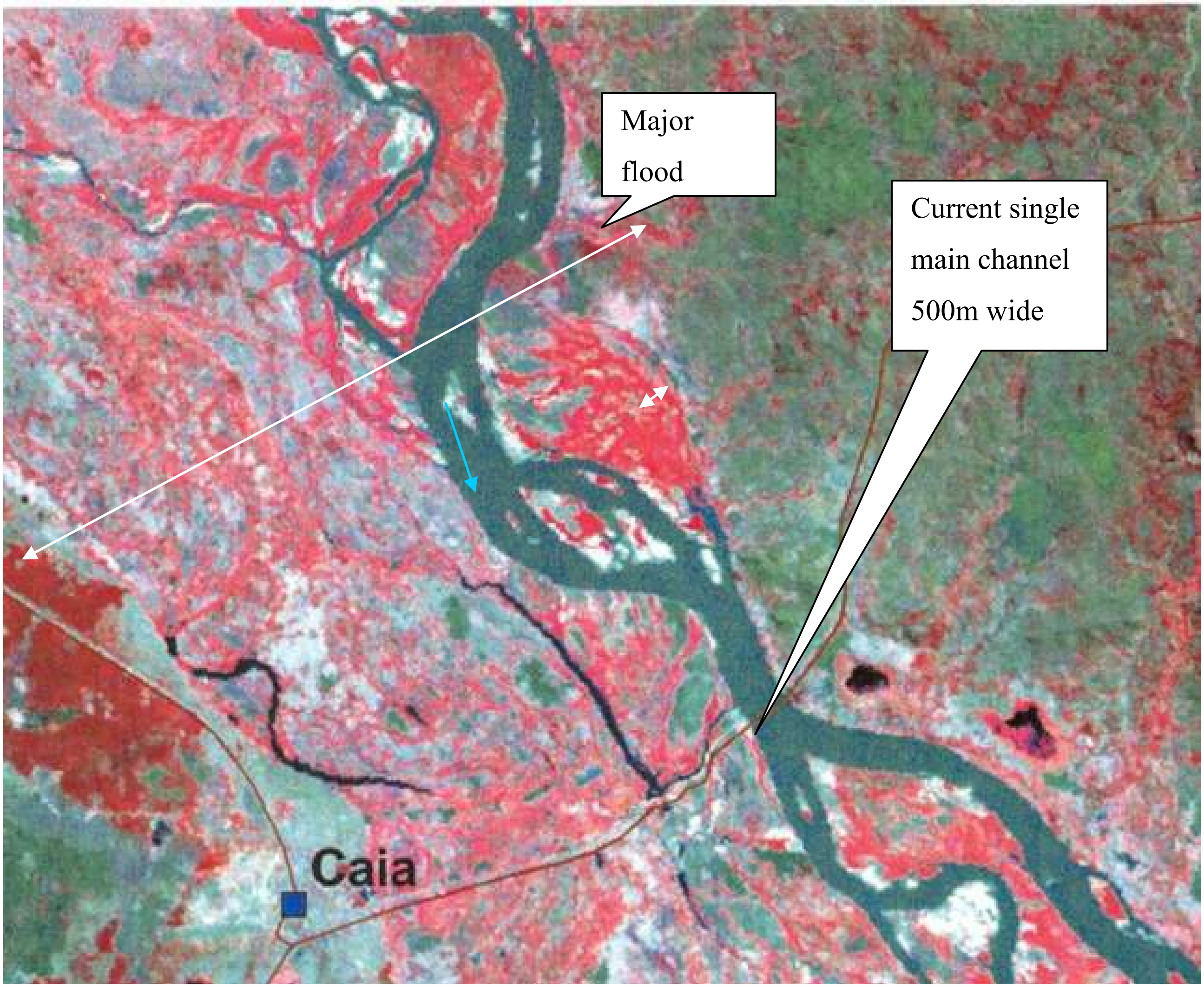


Figure 5.10-4 Satellite image showing dominance of one main channel near Caia (2001).

It is clear that many of the predictions of the original study team were correct. Particularly in the Marromeu Complex, where upstream sectors had experienced widespread encroachment by woody savanna onto the herbaceous floodplain. Meander trains and oxbows were choked, while invasion by the alien plants, Azolla and Eichhornia at least was clear. Bird and mammal life was virtually non-existent compared to the 1970's – the once enormous populations of Cape buffalo, Syncerus cater (over 70 000 head) had virtually disappeared. However, although altered flooding and sediment depletion could be cited for the loss of wildlife, enhanced human access, the civil war, and poaching are more likely causes.

Connectivity of wetlands to the main channel had been disrupted with severe consequences for local artisanal fisheries and avifauna, and only one of the main channels of the Zambezi had relatively newly recruited and healthy mangrove.

Aerial surveys had indicated a 40% loss of mangrove while coastal erosion was obvious. Hoguane (1997) reported that prawn catch rates have declined by 60% between 1978 and 1995, which is directly correlated to falling runoff to the offshore Sofala Bank from the Zambezi. The delta has decreased in size from a width of 600 km to only 150 km since construction of Cahora Bassa Dam. The consistancy of flow imposed by Cahora Bassa Dam can be summarised as little short of catastrophic.

5.11 Minimising the impacts of dam development on the ecosystem and fluvial morphology

5.11.1 Adverse environmental impacts of dam development

The range of adverse environmental and related social impacts that can result from dams is remarkably diverse. While some impacts occur only during construction, the most important impacts usually are due to the long-term existence and operation of the dam and reservoir. Other significant impacts can result from complementary civil works such as access roads, power transmission lines, and quarries and borrow pits. In terms of fluvial morphology the impacts are both upstream (reservoir sedimentation) and downstream river changes which could be down to the ocean.

Mitigation measures can effectively prevent, minimize, or compensate for most adverse impacts, but only if they are properly implemented. Moreover, for some types of negative impacts, at some project sites, the available mitigation measures – even when properly implemented – are inherently unsatisfactory.

The impacts of dams on the environment and fluvial morphology could be minimized by good site selection and operation. The following section provides a brief description of impacts and mitigation options.

5.11.2 Flooding of natural habitats

Some reservoirs permanently flood extensive natural habitats, with local and even global extinctions of animal and plant species. A mitigation option is to establish one or more compensatory protected areas that are managed under the project.

5.11.3 Loss of terrestrial wildlife

The loss of terrestrial wildlife to drowning during reservoir filling is an inherent consequence of the flooding of terrestrial natural habitats. Mitigation options include wildlife rescue efforts. They might be useful for public relation purposes, but they rarely succeed in restoring wild populations (Ledec and Quintero, 2004).

5.11.4 Involuntary displacement

Involuntary displacement of people is often the main adverse social impact of hydroelectric projects. It can also have important environmental implications, such as with the conversion of natural habitats to accommodate resettled rural populations.

The main mitigation measure for physically displaced populations is resettlement, including new housing, replacement lands, and other assistance, as needed. Figure 4.1 shows the relationship between reservoir area and the number of people displaced for different regions of the world. The world average is 60 ha/MW flooded in a reservoir. The median value of people/MW displaced based on World Bank data is 16 (Ledec and Quintero, 2004). All the African dams considered have a high area/MW ratio (Figure 4.2) and many people have been displaced, which is due to the variable climatic conditions which require a relatively large storage capacity and densely populated areas.

5.11.5 Loss of cultural property

Cultural property, including archaeological, historical, pale ontological, and religious sites and objects, can be inundated by reservoirs or destroyed by quarries, borrow pits, roads, or other works.
Structures and objects of cultural interest should undergo salvage after community consultation, when feasible, through scientific inventory, physical relocation, and documentation and storage in museums or other facilities.

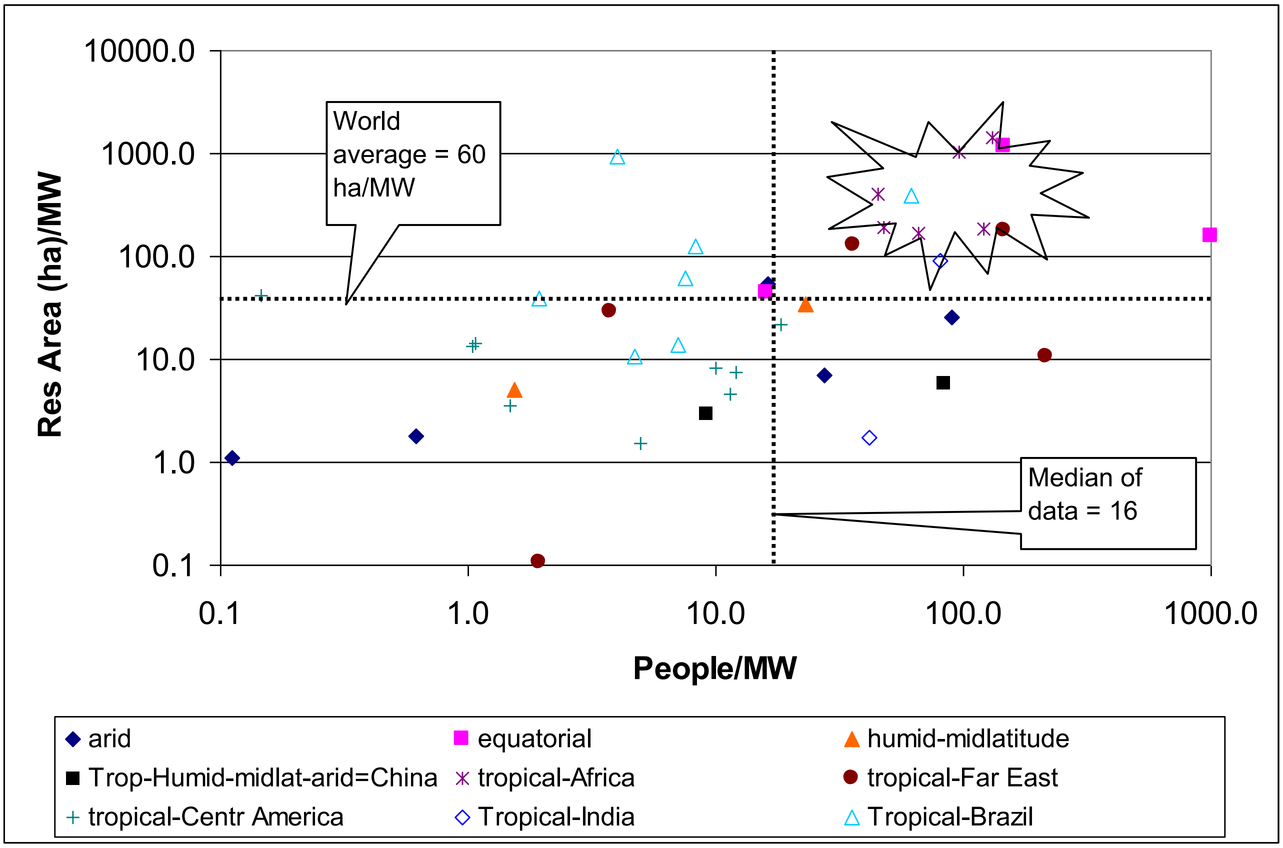


Figure 5.11-1 The relationship between reservoir area and number of people displaced

Projects with a small reservoir surface area (relative to power generation) tend to be most desirable from both an environmental and social standpoint, in part because they minimise natural habitat losses as well as resettlement needs.

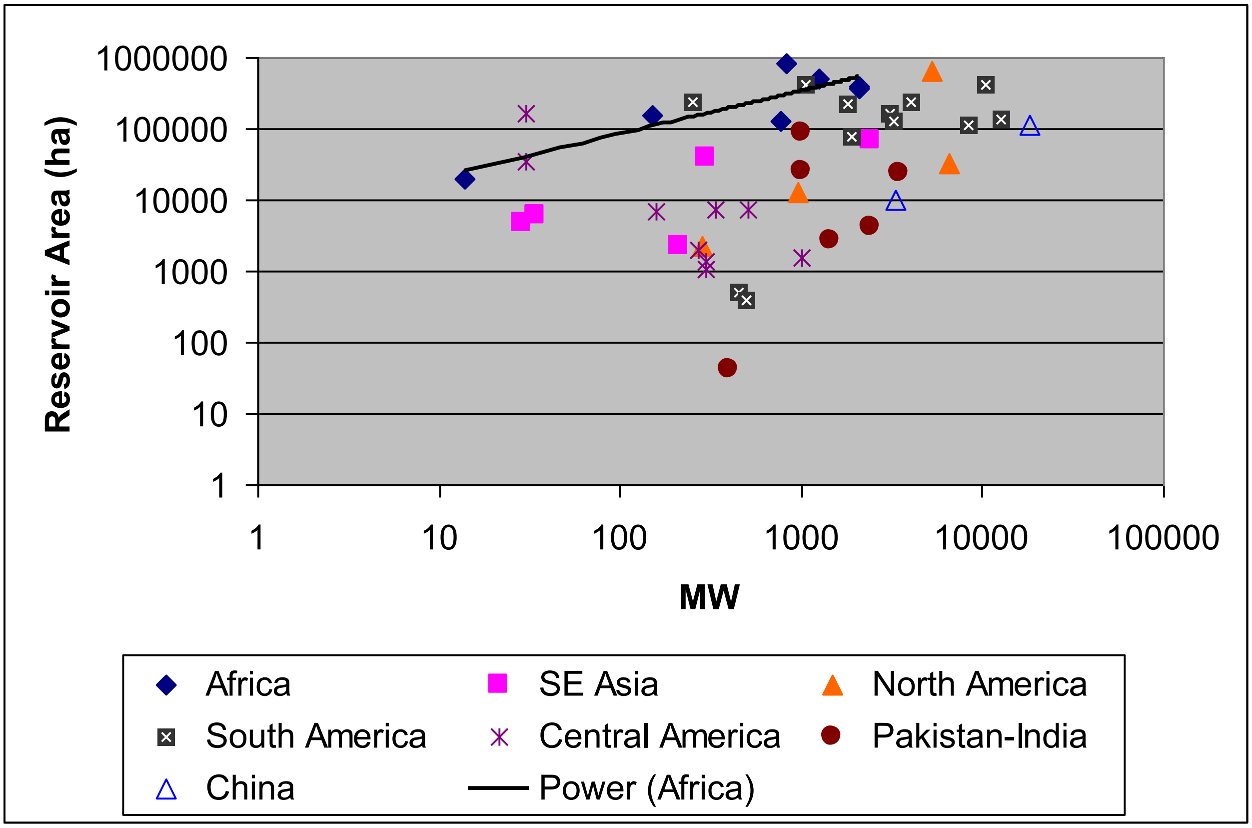


Figure 5.11-2 The relationship between reservoir area and power generation

5.11.6 Deterioration of water quality

The damming of rivers can cause serious water quality deterioration, due to the reduced oxygenation and dilution of pollutants by relatively stagnant reservoirs (compared to fast-flowing rivers), flooding of biomass (especially forests) and resulting underwater decay, and/or reservoir stratification (where deeper lake waters lack oxygen). Mitigation Options. Water pollution control measures (such as sewage treatment plants or enforcement of industrial regulations) may be needed to improve reservoir water quality.

5.11.7 Downriver fluvial morphological

Major downriver hydrological changes can destroy riparian ecosystems dependant on periodic natural flooding, exacerbate water pollution during low-flow periods, and increase saltwater intrusion near river mouths. Reduced sediment and nutrient loads can increase river-edge and coastal erosion and damage the biological and economic productivity of rivers and estuaries. Induced degradation of rivers below dams can kill fish and other fauna and flora, and damage agriculture and water supplies.

These adverse impacts can be minimized through careful management of water releases and in this regard variability is very important. Objectives to consider in optimizing water releases from the turbines and spillways include adequate downriver water supply for riparian ecosystems, reservoir and downriver fish survival, reservoir and downriver water quality, aquatic weed and disease vector control, irrigation and other human uses of water, downriver flood protection, recreation, and of course power generation. From an ecological standpoint, the ideal water release pattern would closely mimic the natural flooding regime.

5.11.7.1The Cahora Bassa Dam case study

Variability is a key component of healthy riverine ecosystems. In the Cahora Bassa case, flow regulation has radically reduced the spatial and temporal dynamics of the river. Whilst one may not be able to rehabilitate the entire river to its original ‘pre-regulated state’s, the condition of several key ecological functions would be improved with prescribed flood events. Releases of water from the dam to ensure significant floodplain inundation would ensure the reinstatement of some ecological functioning.

Ideal flood and low flows, seasonal patterns of sediment transport desired, water quality states, and minimum requirements for fish-spawning cues can be generated for a particular river or river zone in relation to an identified water project using system- and site-specific knowledge, and the best available expert opinion. In Africa most rivers have not been developed as extensively as elsewhere in the world and the responsibility is therefore even higher to limit the impacts of new developments as much as possible and this can only be done with state-of-the-art mathematical models (1D and 2D) to simulate longterm fluvial processes, with local expert knowledge. Managed flood releases for river channel maintenance should be designed to maintain the pre-dam sediment load-discharge relationship along the river at different baseline sites.

In a rule-of–thumb approach, Wilson (1997) calculated that some 49km3 out of a total reservoir storage capacity of 63 km3 (this seems a high ratio), are available annually from lake Cahora Bassa without loss of power production. Further, with correct intra-annual variability, a drop in present dry season flows from the reservoir by 3 km3/month could stimulate prawn production by some $30 million /year.

Such flow variations would have to be coupled to an exhaustive social programme, for the newly formed islands and stabilised margins of the lower river now have large human populations.

5.11.8 Water-related diseases

Some infectious diseases can spread around hydroelectric reservoirs, particularly in warm climates and densely populated areas. Some diseases are borne by water-dependant disease vectors, others are spread by contaminated water, which frequently becomes worse in stagnant reservoirs than it was in fast-flowing rivers. In Africa bilharzia, malaria and cholera kill millions of people every year. Public health measures should include preventative measures, monitoring of vectors and disease outbreaks, vector control, and clinical treatment of disease cases, as needed.

5.11.9 Fish and other aquatic life

Hydroelectric projects often have major effects on fish and other aquatic life. Reservoirs positively affect certain fish species (and fisheries) by increasing the area of available aquatic habitat. However, the net impacts are often negative, especially in the downstream river. Management of water releases are required for the survival of certain species in and below the reservoir.

5.11.10 Floating aquatic vegetation

Floating aquatic vegetation can rapidly proliferate in eutrophic reservoirs, causing problems such as (a) degraded habitat for most fish and other aquatic species, (b) improved breeding grounds for mosquitoes and other nuisance species and disease vectors, (c) impeded navigation and swimming, (d) clogged electromechanical equipment at dams, and (e) increased water loss from some reservoirs. Pollution control and pre-impoundment selective forest clearing will make reservoirs less conductive to aquatic growth. Physical removal or containment of floating aquatic weeds is effective but imposes a high and recurrent expense for large reservoirs. Biological control is an effective instigation measure.

5.11.11 Greenhouse gasses

Greenhouse gasses are released into the atmosphere from reservoirs that flood forests and other biomass, either slowly or rapidly. Greenhouse gasses are widely considered the main cause of human-induced global climate change. Gas release from reservoirs can be reduced by salvage of commercial timber and fuelwood.

5.11.12 Impacts of complementary civil works.

Complementary civil works can induce major land use changes – particularly in the case of access roads, power transmission lines, quarries and borrow pits and associated development plans, but the effects are usually localized. The siting of these works should be in the environmentally and socially least damaging areas.

Other aspects:

- Water quality such as turbidity and colour for potable use
- Quality of sediments in reservoir
- Algal growth related to sedimentation
- Retirement, Etc.
-

5.11.13 Reservoir Sedimentation

Over time, live storage and power generation are reduced by reservoir sedimentation, such that much of some projects' hydroelectric energy might not be renewable over the long term, since most dams are only designed for a 50 to 100 year live storage life.

5.11.13.1 Measures to limit the sediment yield

a) Soil-water conservation in the catchment
Whereas it would be wonderful if large scale catchment management policies could serve to limit reservoir sedimentation and to practise soil conservation at the same time, success in this regard has been very limited. Some of the decreases in sediment loads which have been observed are due to depletion of erodible top soils rather than successes with soil conservation measures. It is also very difficult to get governments to apply strong soil conservation measures as these are generally expensive and unpopular.

It should be remembered that soil erosion is a natural phenomenon. In South Africa erosion gullies similar to the one shown in Figure 2-1 were observed as long back as 1830 under near natural conditions.

Figure 5.11-3 Erosion gully

Soil and water conservation programmes were implemented in large catchments from the 1950s. These included farming practises, control of overgrazing, and the control of gully erosion. The latter engineering measures were introduced to control erosion but it is doubtful whether it was successful in limiting the long-term sediment yield. Figure 2-2 shows a silted small check dam. The clear water spilling from check dams scoured sediments downstream and degraded the riverbed. Once the small reservoirs became filled with sediment to the spillway elevation, bypassing with new gully erosion often occurred. Generally it is now believed that check dams are not cost-effective in semi-arid conditions to limit sediment yields (Basson and Rooseboom, 1997). Apart from the problems mentioned above, the fine sediment loads transported during the dominant flood which is typically the 1:10 year flood in semi-arid conditions, need long distances to become deposited in slow flowing conditions, which can only be attained with extremely large and costly structures.

Figure 5.11-4 Check dam

Terraces on steep slopes have been implemented in Europe and China, but are not always successful. Figure 2-3 shows terraces in the Yellow River catchment where it is very difficult to control the gulley erosion. In semi-arid regions terracing can however permanently damage the catchment. Figure 2-4 shows such a terraced catchment in Algeria, 30 years after implementation.

Figure 5.11-5 Terraces and 300 m deep gulley erosion in the Yellow River catchment, China

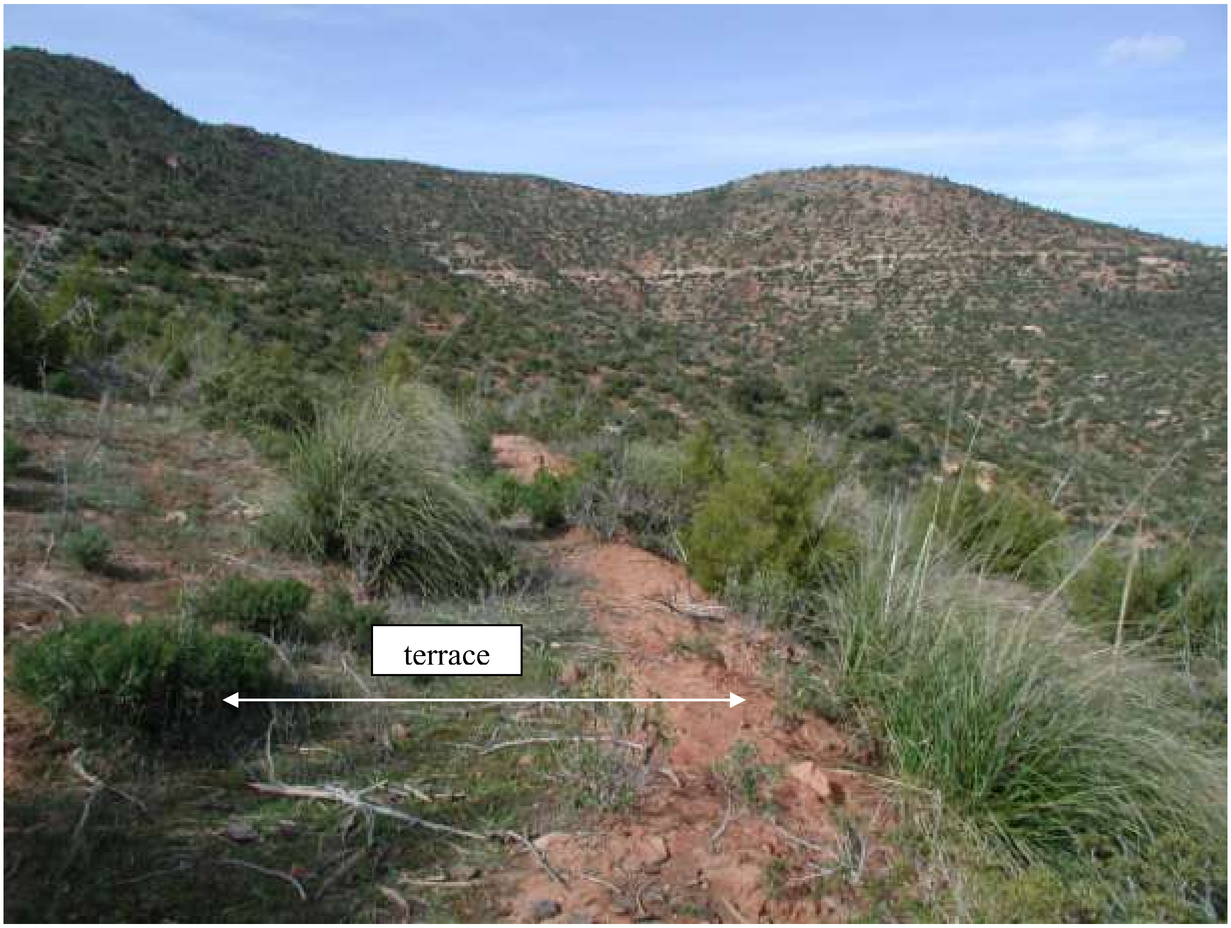


Figure 5.11-6 Terraced catchment in Algeria

The implementation of soil-water conservation programmes is important to limit erosion. The effectiveness of these programmes to reduce the long-term sediment yield in large catchments is however doubtful. This is because there is a poor understanding of the interrelationship between soil erosion and sediment yield in large catchments. Except in very small catchments (farm scale), catchment management should therefore not be relied on as the only means of limiting reservoir sedimentation.

b) Vegetation screens

Vegetation screens upstream of a reservoir were at one stage regarded as one of the most effective ways to reduce sediment inflow to a reservoir Vegetation control is however not practical in arid conditions and leads to high evapo-transpiration.

c) Sediment diversion (warping)

The diversion of sediment-laden flows upstream of reservoirs for warping and irrigation is practised on a large scale in China where floods transport high concentrations of very fine sediment rich in nutrients for crops, thereby creating new fertile farm land and at the same time reducing reservoir sedimentation.

d) Sediment bypassing

Where the topography allows it a bypass canal or tunnel can be constructed to transport high sediment loads past a reservoir. Nagle Dam in South Africa was constructed in 1950 with a bypass and the main reservoir has remained relatively free of sediment. The bypass has a large discharge capacity of about 2000 m^3/s (Figure 5.11-7).

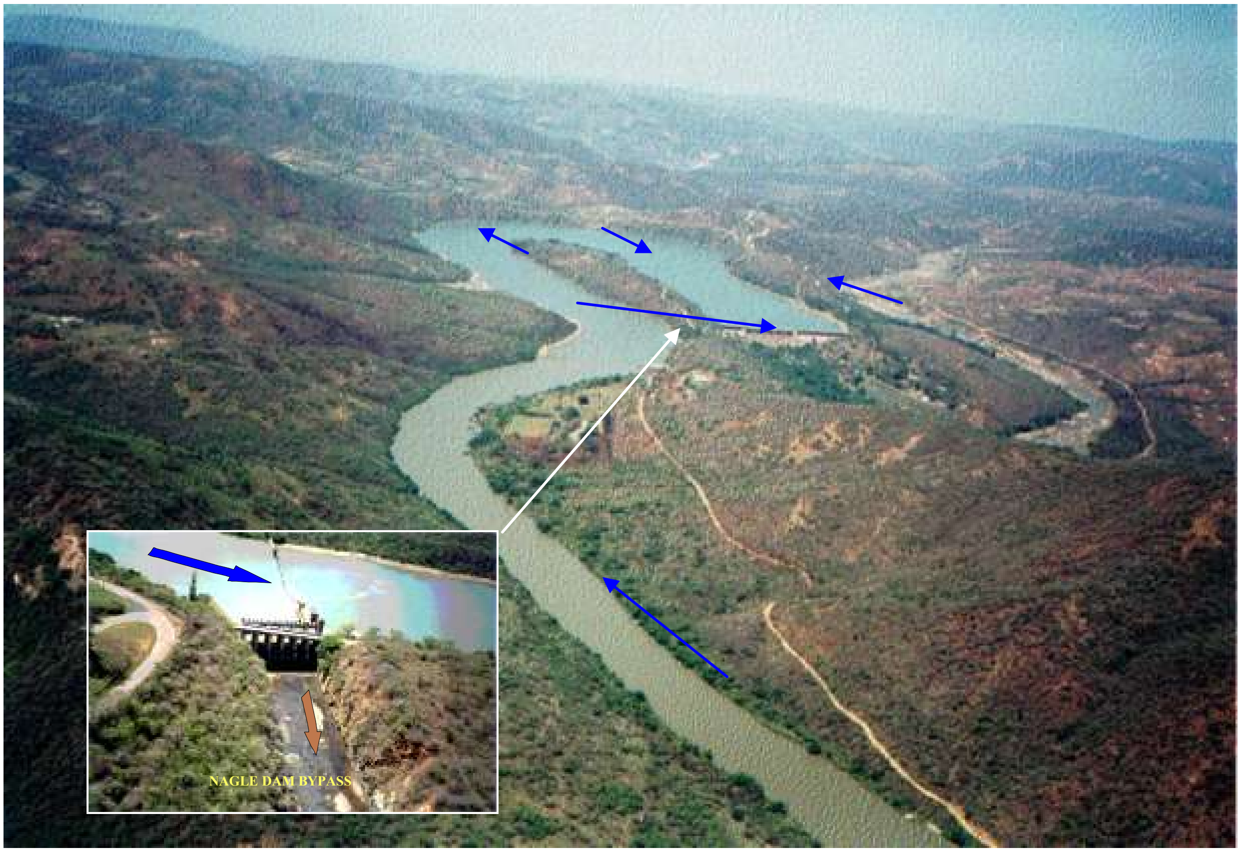


Figure 5.11-7 Nagle Dam bypass

e) Off-channel storage reservoir

On rivers with high sediment loads diversions to off-channel reservoirs located on tributaries can be used. Transfer to the off-channel dam is typically achieved through a low head river pumping station via a sand trap, and pumping can be stopped during periods of high sediment transport in the river. Canals or tunnels with water diversion under gravity are also used.

5.11.13.12 Methods to pass sediment loads through a reservoir

a) Sluicing

Successful sluicing depends on the availability of excess water and relatively large bottom outlets at the dam. For successful flushing the reservoir capacity-mean annual runoff ratio should be quite small, say less than 0.2 year (<0.03 year in semi-arid regions). Free outflow conditions are preferable, but not a requirement as with flushing, and only partial water level drawdown is required as long as the sediment transport capacity through the reservoir is high during a flood.

b) Density current venting

Density currents, also known as turbidity currents, form under very specific boundary conditions and require a high percentage of fine suspended sediment and a relatively steep reservoir bed slope for their creation. After plunging of the sediment laden stream, all the coarse particles are deposited and the fines can be carried over long distances towards the dam.

Theory is available to predict the formation and sediment transport of density currents (Basson and Rooseboom, 1997), and should be applied at all reservoirs to predict possible density current formation under the various operational conditions. Turbidity sensors should also be installed at several elevations upstream of the dam wall for management of density currents by releasing high sediment concentrations through low level outlets.

5.11.13.3 Measures to remove deposited sediment from the reservoir

a) Flushing

Flushing can be a very effective way to remove accumulated sediment deposits from a reservoir. As with sluicing, excess water is required with large low-level outlets capable of passing say the 1:5 year flood under free outflow conditions. Successful flood flushing is carried out at Phalaborwa Barrage on the Olifants River, South Africa, where 22 large, 12 m wide radial gates were installed, covering the whole width of the river (Figure 5.11-8). The reservoir has been operated since the 1960s, and a long-term capacity in the order of 40 % of the original capacity is being maintained.

Figure 5.11-8 Phalaborwa Barrage flood flushing (1996)

Retrogressive erosion makes flushing a highly effective method to remove large quantities of sediment (Figure 5.11-9).

Figure 5.11-9 Retrogressive erosion during flushing at Elandsdrift Reservoir, South Africa

At some other reservoirs flushing is less effective even though the capacity-MAR ratio is less than 1 %., for example the case of Welbedacht Dam, South Africa, which has 5 large radial gates but which are not located at the river bed but 15 m above it. After 20 years of operation, 85 percent capacity was lost and today only about 5 million m^3 of storage capacity remains and this is with regular flushing during floods larger than 400 m^3/s.

Effective flushing requires:

- Excess water
- Suitably large low level outlets
- A steep, narrow reservoir basin
- Judicious operation

Figure 5.11-10 shows the Xialongdi Dam on the Yellow River, China, sediment release conduits in operation during commissioning tests.

Figure 5.11-10 Xialongdi Dam, China, during commissioning test

Flushing operation requires excess water to be effective and in most cases this means a reduction in water yield. Reservoir conservation by using flushing or sluicing are therefore in direct conflict with the water demands such as irrigation or hydropower.

The effect of a reservoir conservation measure such as flushing also varies depending on the hydrology. Two case studies are discussed here to illustrate the effect of flushing on the water yield of a reservoir in the Yellow River catchment, China, and in the semi-arid region of Algeria in northern Africa, respectively.

By using a 70 year monthly flow record of the Yellow River at Sanmenxia, the firm water yield/mean annual runoff (MAR) ratio was calculated for various reservoir storage capacities as shown in Figure 5.11-11. The same graph also shows the water yield relationship for an Algerian reservoir. (Firm yield is the maximum draft on the reservoir for the demand on the reservoir to fail at a risk of say only once in 50 years).

For the Chinese case study it seems that the runoff variability is relatively small and that a storage capacity of about 50 % MAR would provide a near optimum firm yield. In the semi-arid conditions of Algeria the required storage capacity could be 100% MAR due to the variable hydrological conditions. At a storage capacity/MAR ratio of 0.5, the firm water yield in China is 74%MAR, while in Algeria it is only 37%MAR which is typical for semi-arid conditions, and this is without flushing. The effect of flushing on the water yield has to be considered for these case studies.

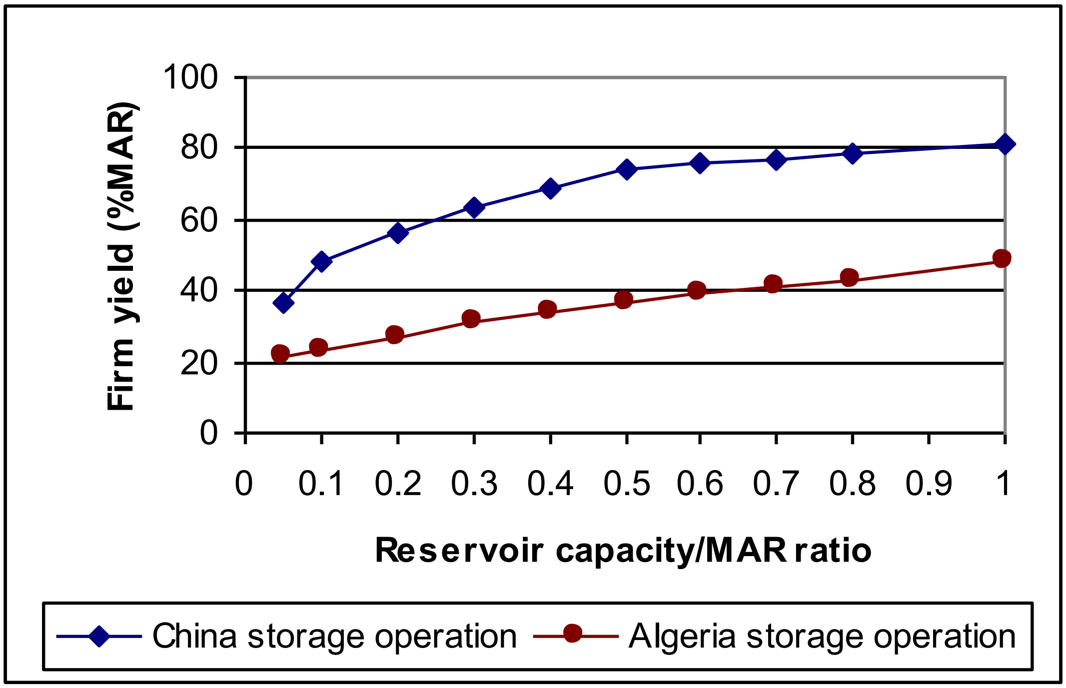


Figure 5.11-11 Water yield-storage capacity relationship without flushing

Typical climatic conditions at small reservoirs in China allow seasonal flushing. This means that the reservoir water level is drawn down during the high flow season to allow floods to pass freely through large low level outlets for say one or two months, and the reservoir fills again at the end of the rainy season with relatively low sediment loads. The observed monthly runoff distribution of the Yellow River is shown in Figure 5.11-12, with the complete observed river flow record shown in Figure 5.11-13. A number of simulations were carried out with the Chinese hydrological data to determine the effect of flushing on the water yield and the results are shown in Figure 5.11-14. Flushing every year during July or every year during July and August was firstly considered but it was found that the impact on the water yield is relatively high. As alternative, flushing at an assurance of 80 % of the time (4 out of 5 years (July) on average) was also simulated and is considered more realistic.

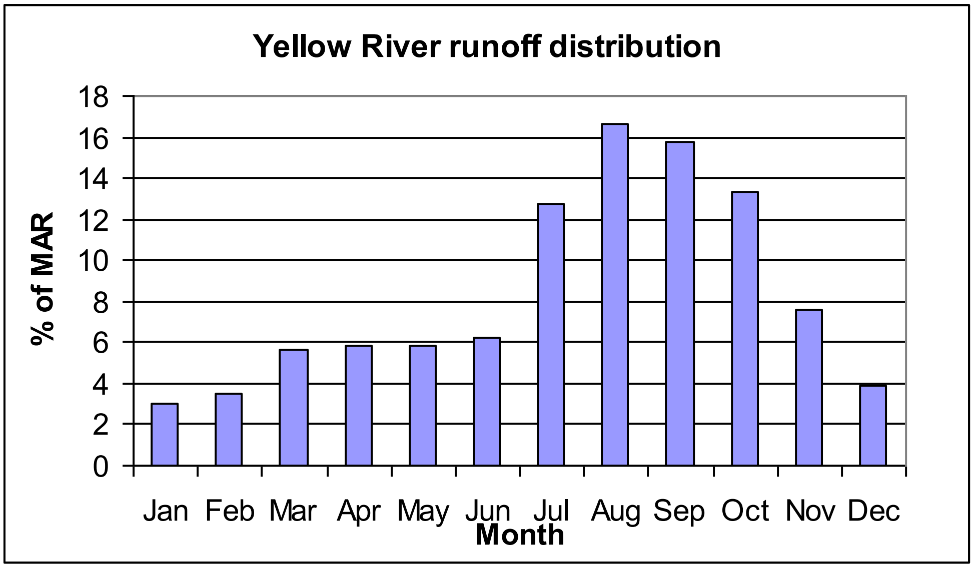


Figure 5.11-12 Yellow River monthly runoff distribution

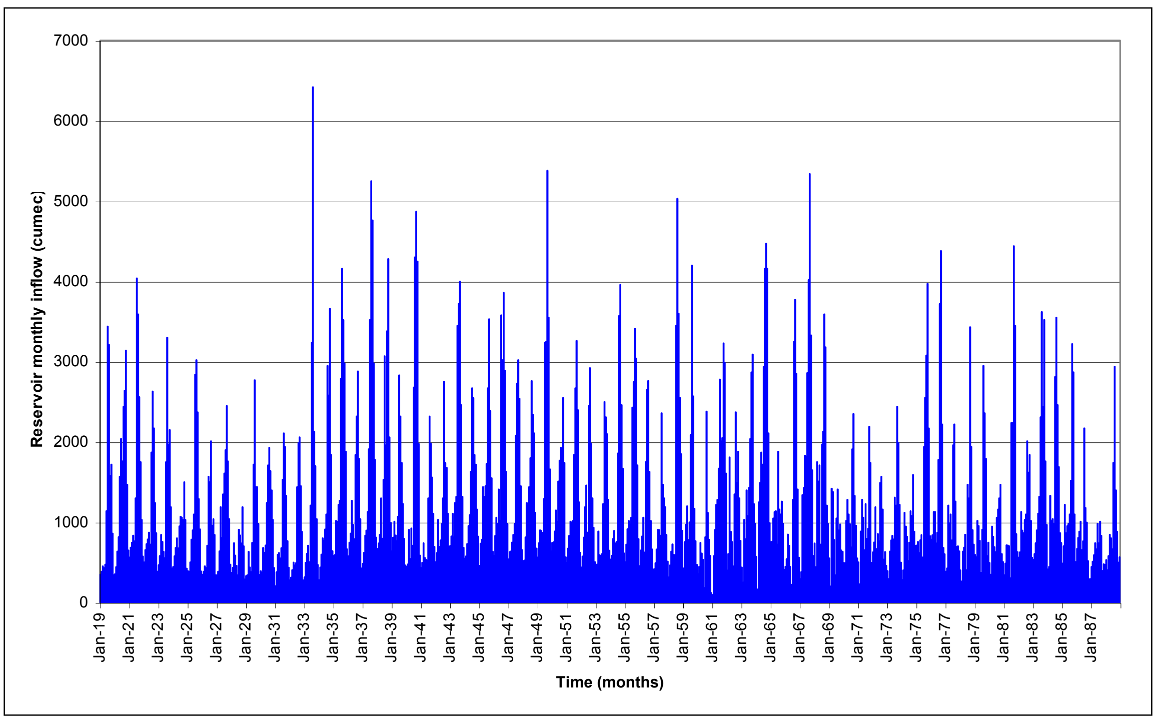


Figure 5.11-13 Yellow River observed monthly flows used in simulations

Flushing (80 % of July's) indicates that up to a storage capacity-MAR ratio of 0.2 the same firm yield can be obtained as without flushing. This is because excess water would spill under storage conditions while with flushing operation, spillage is converted to bottom releases at the dam. Other months such as August or September were also investigated and similar results were found. At a capacity-MAR ratio of 0.5 the reduction in firm yield from storage operation (no flushing), to one month flushing per year is 26 %. At higher capacity-MAR ratios the firm yield with flushing for one month per year remains more or less constant at 54% MAR.

When flushing is carried out over two months during July and August at 80 % assurance, the water yield drops considerably when the reservoir capacity-MAR ratio is less than 0.3. At higher capacity-MAR ratios the reduction in water yield is only 10% (from 51% MAR to 46% MAR) for one month and two month flushing periods per year at 80 % assurance. For this specific case study it therefore seems that for capacity-MAR ratios < 0.3, one month/year flushing is more favourable in terms of water yield, while at capacity-MAR ratios > 0.3, two months/year flushing periods would be more favourable in terms of water yield and passing sediment through the reservoir.

So far the actual sediment loads of the Yellow River were not considered in the analysis to determine whether one or two month flushing durations per year would be sufficient. Figure 5.11-15 shows expected reservoir life when typical sediment loads of the Yellow River are considered with storage operation, one month flushing per year and 2 month flushing per year. It is clear that the actual sediment yield is so high that at least two months annual flushing is required to provide more than 100 year life for the reservoir. In addition Figure 5.11-16 shows that when the storage capacity-MAR ratio is less than about 13 %, the two month annual flushing operation will provide a sustainable solution. This is exactly what was found with Sanmenxia Reservoir operation in the field. Initially the Sanmenxia Reservoir capacity-MAR ratio was more than 20 %, but since reconstruction of the outlets and modified operation in the 1960s the capacity-MAR ratio varied between 13 % and 6 %.

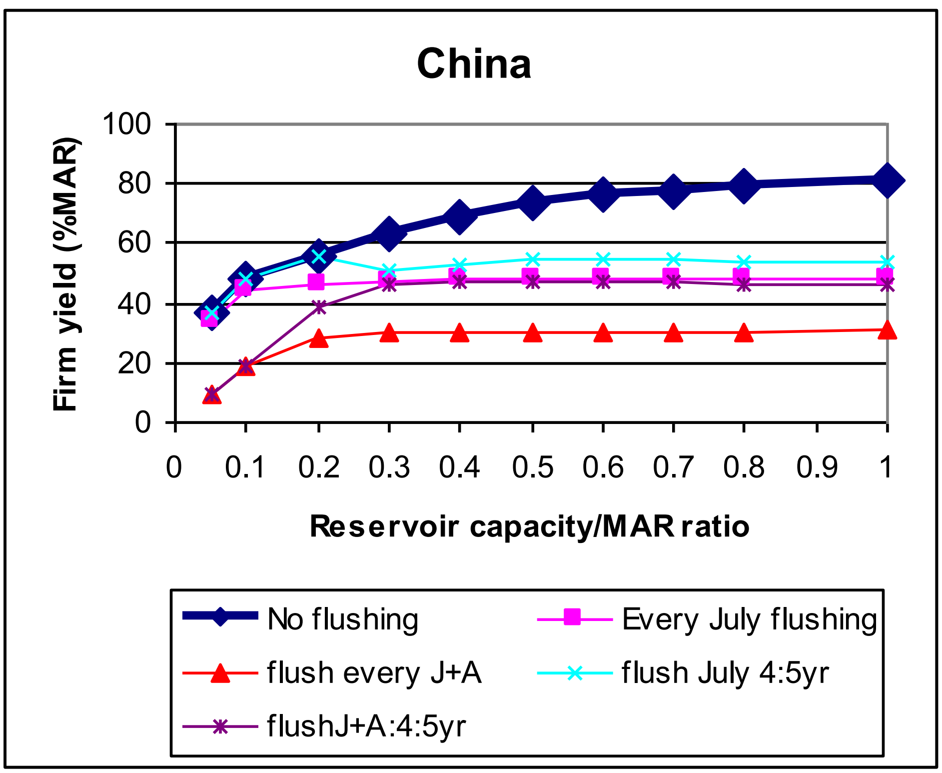


Figure 5.11-14 Water yield-storage capacity relationship for Chinese case study with flushing

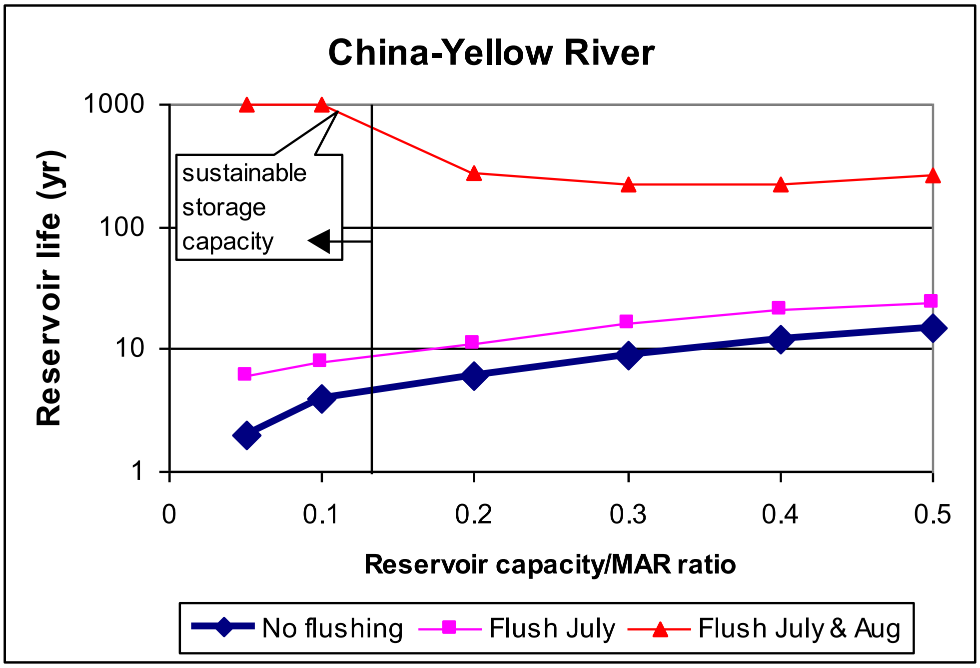


Figure 5.11-15 Reservoir operation versus reservoir life

Figure 5.11-16 shows the firm yield range which can be achieved with flushing for 2 months/year, considering the sediment yield. The maximum firm yield with flushing is 45 % MAR, but the life of the reservoir can be extended if the water demand is reduced, giving a firm yield of 31 % MAR.

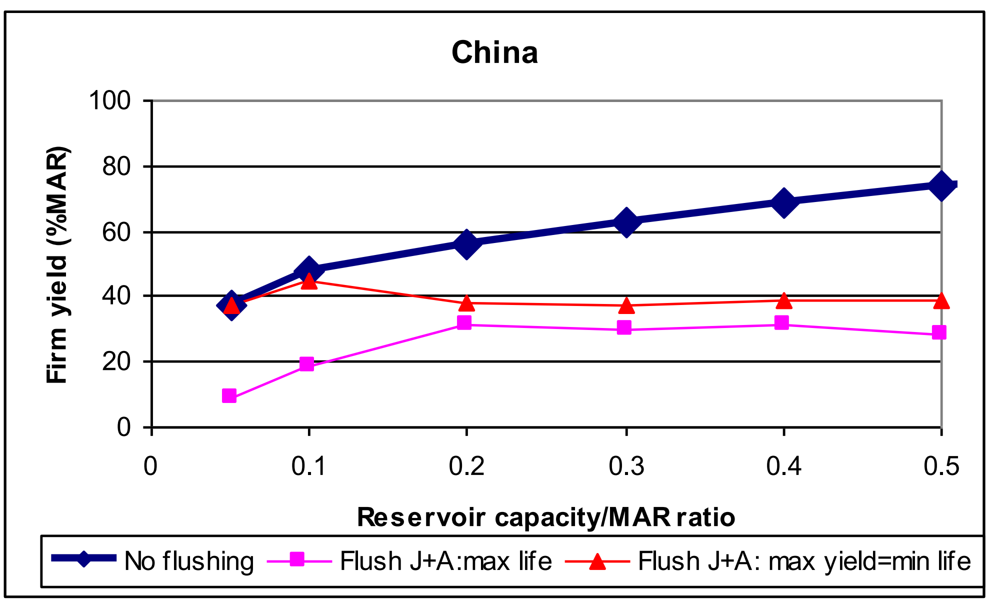


Figure 5.11-16 Sustainable reservoir operation and water yield

Observed annual reservoir inflows for an Algerian river is shown in Figure 5.11-17. It is clear that the inter annual variation is much higher than in the case of the Chinese data used.

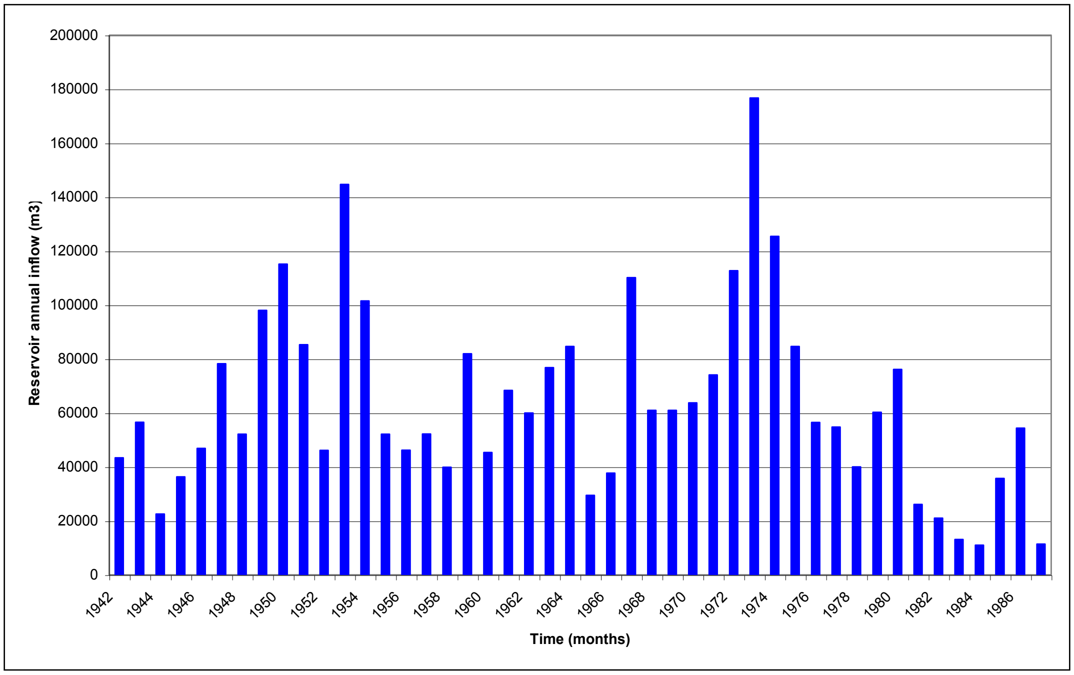


Figure 5.11-17 Observed annual reservoir inflow for Algerian case study

The impact of flushing on the Algerian case study is shown in Figure 5.11-18. Flushing for one month per year at 80 % assurance gives the same yield as storage operation for a reservoir capacity-MAR ratio up to 0.4 which is higher than the Chinese case study, but the firm yield %MAR values are relatively much less in the Algerian case. At capacity-MAR ratios larger than 0.4 the firm yield is considerably less than under storage operation conditions and it is therefore highly likely that the mode of operation would be storage operation. One problem in semi-arid conditions is that high sediment load floods are difficult to predict and therefore flushing operation is often practiced based on individual floods than on a specific month in the year. For flood flushing during individual floods, water level drawdown is required with a flood warning system, and the storage capacity-MAR ratio is usually even smaller than with seasonal/monthly flushing.

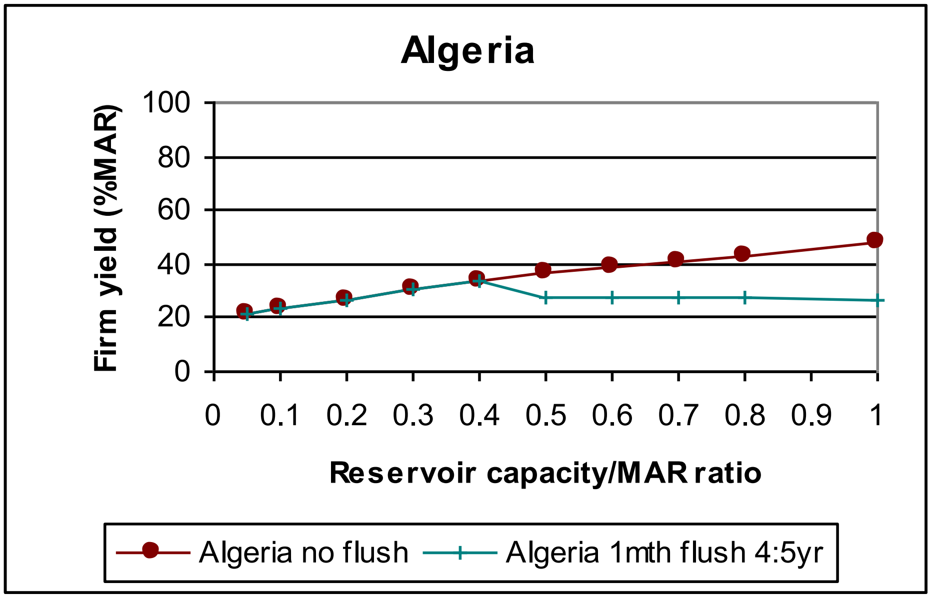


Figure 5.11-18 **Water yield-storage capacity relationship for Algerian case study with flushing**

In the Yellow River case study used so far the observed sediment yield of 2300 t/km^2.a was used which is relatively high compared with many other rivers. If the same hydrology is considered, but a sediment yield of 25 % of the Yellow River, shorter duration flushing is required, and the firm yield is higher as shown in Figure 5.11-19. By flushing only in July, it is possible to achieve a firm yield of 50 % MAR, versus the 31 % MAR achieved at the high sediment yield.

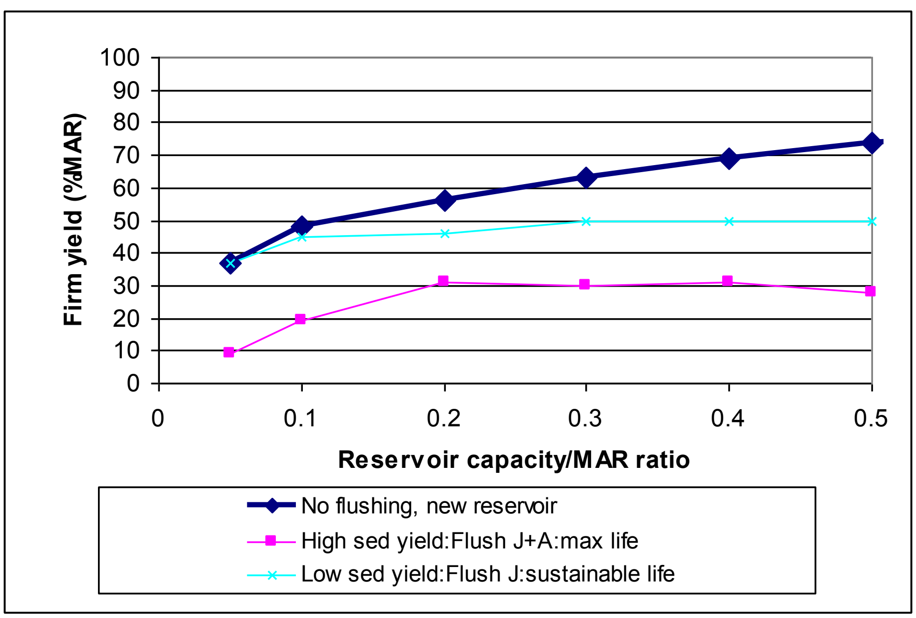


Figure 5.11-19 **Water yield with shorter duration flushing when the sediment yield is smaller using Chinese data**

b) Excavation
Dredging to recover lost storage capacity has been carried out only on a limited scale worldwide mainly because of the high costs and the environmental problems associated with disposal of the dredged sediments.

At Mbashe Dam, South Africa, a 30 m high concrete structure constructed in the 1980s for hydropower generation, most of the original capacity of about 9 million m³ was lost within two years (Figure 4-3). At the end of the 1980s two hydraulic dredgers were used to try and remove some of the sediment. Sediment disposal was immediately downstream of the dam into the river. A dredging efficiency of only 16 % was achieved due to mechanical breakage, underestimation of the cohesiveness of the sediment, construction equipment left behind in the reservoir, and limited sediment availability at the cutter due to the cohesiveness. About 2 million m³ of sediment was removed over a period of 3 years, but this was much less than the inflowing sediment load. Hydraulic flushing would have been a much more effective measure, but only a small 5x5 m bottom outlet was installed which is too small to allow free outflow conditions.

At Mkinkomo Reservoir in Swaziland, also a hydropower reservoir, dredging of 0.3 million m³ of sediment was first carried out and deposited over the dam into the downstream river with the idea that it would be washed away during floods. Irrigators downstream however protested due to the loss of pools in the river and environmental considerations, and the disposal site was moved to above full supply level next to the reservoir. Sediment was placed in 0.5 m layers and allowed to dry for say one month before the next layer was placed on top. Clear dredging water was allowed to flow back to the reservoir after sediment deposition in the disposal area. In total about 1.5 million m³ sediment was dredged over a period of 2 years.

Dredging is highly specialized and site specific equipment is required. It is generally found that in water depths of less than 30 m hydraulic cutter-suction and bucket wheel dredgers are most effective, with transport through floating pipeline and fixed pipeline on land. The length of the pipelines is also important since it affects the dredging range and efficiency. It should be noted that electric power instead of diesel power often reduces the cost of dredging by half.

Mechanical excavation is usually much more expensive than dredging due to high transport costs and double handling.

Siphon dredging (or hydro-suction) with sediment disposal into the river is cheap, but creates ecological problems. The pipe length is also limited due to the available head and high flow velocities are required in the pipe, if booster pumps are not used.

Sediment removal by dredging to recover lost storage capacity should be seen as a last resort as the removal of sediment deposits is extremely expensive and disposal creates new social and environmental problems.

5.11.13.4 Sedimentation compensation measures

a) Dam raising
Dam raising in many cases provides an economical solution to regain storage capacity lost due to sedimentation. The raising options which are typically considered are fixed uncontrolled spillways, crest radial gates, automatic crest gates or fusegates. Uncontrolled spillways are however preferred from a dam safety perspective.

The incremental water yield obtained from the additional capacity created by raising is limited in semi-arid regions by the large open water body and high associated evaporation losses. For example at Gariep

Dam, South Africa, the mean annual evaporation losses could increase from 10 m^3/s to 15 m^3/s if the dam is raised by 5 m.

b) New dams

Dam sites should be selected in regions with relatively low sediment yields. The upper reaches usually have a relatively high runoff, while the sediment loads are small. This is however not always possible due to the location of the power demand centres and the availability of dam sites. In the past long and wide reservoir basins were usually selected to create maximum storage capacity, but under certain conditions where sediment flushing during floods is possible, a narrow reservoir would be more suitable in providing a sustainable solution.

c) Design for sedimentation

A storage operated (minimisation of spillage) reservoir is typically sized to accommodate the expected 50-year sediment volume allowing for trap efficiency. This volume is considered as dead storage in the yield analysis, which means that only after 50 years of operation will sedimentation start to impact on the water yield. In practice sedimentation first occurs in the live storage zone with more than 80 percent of sedimentation taking place in this zone. The dams are however designed to withdraw water from the dead storage zones allowed for sedimentation.

d) Augmentation from adjacent catchments

Regulation of runoff and sedimentation control requirements in a reservoir are often in conflict. Transfer of water from adjacent catchments can provide a solution to sedimentation control in an existing reservoir if the scheme is economically feasible and if the donor catchment can provide sufficient excess runoff.

6. Development of Guidelines to Determine and Limit the Impacts of Dams on the Downstream River Morphology

The major downstream impacts of dams are a reduction of the magnitude and frequency of flood peaks, changes in flow duration and reduced downstream sediment supply due to the trapping of sediments in the reservoir. These changes can lead to riverbed degradation close to the dam and aggradation further downstream, as the river strives for a new equilibrium. In order to reverse some of the changes that have taken place, or prevent major changes from occurring, researchers have been attempting to define a regulated flow regime, which will have much the same effects as the natural pre-dam flow regime. The problem, however, is to define those flows that form and maintain the river channel and the floodplain. The relative importance of different flows can best be evaluated by determining the amount of sediment transported by each. The discharge that transports the greatest amount of sediment over time is termed the effective discharge and identifying that discharge could help to determine a flow regime that will maintain the river in a natural or at least equilibrium state.

6.1 Determination of the Effective Discharge (Dollar *et al.*, 2000)

The method outlined by Dollar *et al*. (2000) to determine the effective discharge is as follows:

- Daily flow data are used to generate flow duration curves.
- The flow duration curves are divided into individual flow classes. It is assumed that the flows equalled or exceeded 10% of the time or less are most likely the most significant in terms of sediment transport. Therefore the flows from the 99.99% equalled or exceeded to the 10% equalled or exceeded are divided into 10% duration flow classes. The flow exceedences less than this are divided into flow class durations of 5%, 4%, 0.9% and 0.09%, respectively.
- The geometric mean of each flow class is then calculated.
- For each flow class the sediment concentration is calculated using a sediment transport equation like Engelund and Hansen or Yang.
- The sediment transported for each flow class is thus determined and expressed as a percentage of the total sediment transported.
- The effective discharge can then be determined.

This approach is used to determine the effective discharge of the Pongola River in its natural state. The flow record used contains 39 years of flow data. Engelund and Hansen's total load equation was used and the all the necessary parameters obtained from a surveyed cross-section, with d_{50} = 0.12mm. The use of the sediment transport equation does, however, not take into consideration that the sediment transport may be supply limited. For this reason a sediment rating curve was used to determine the sediment load and the results were compared to those obtained by utilizing Engelund and Hansen's sediment transport equation. The results are illustrated in **Figure 6.1.1**, and summarised in **Table 6.1.1**.

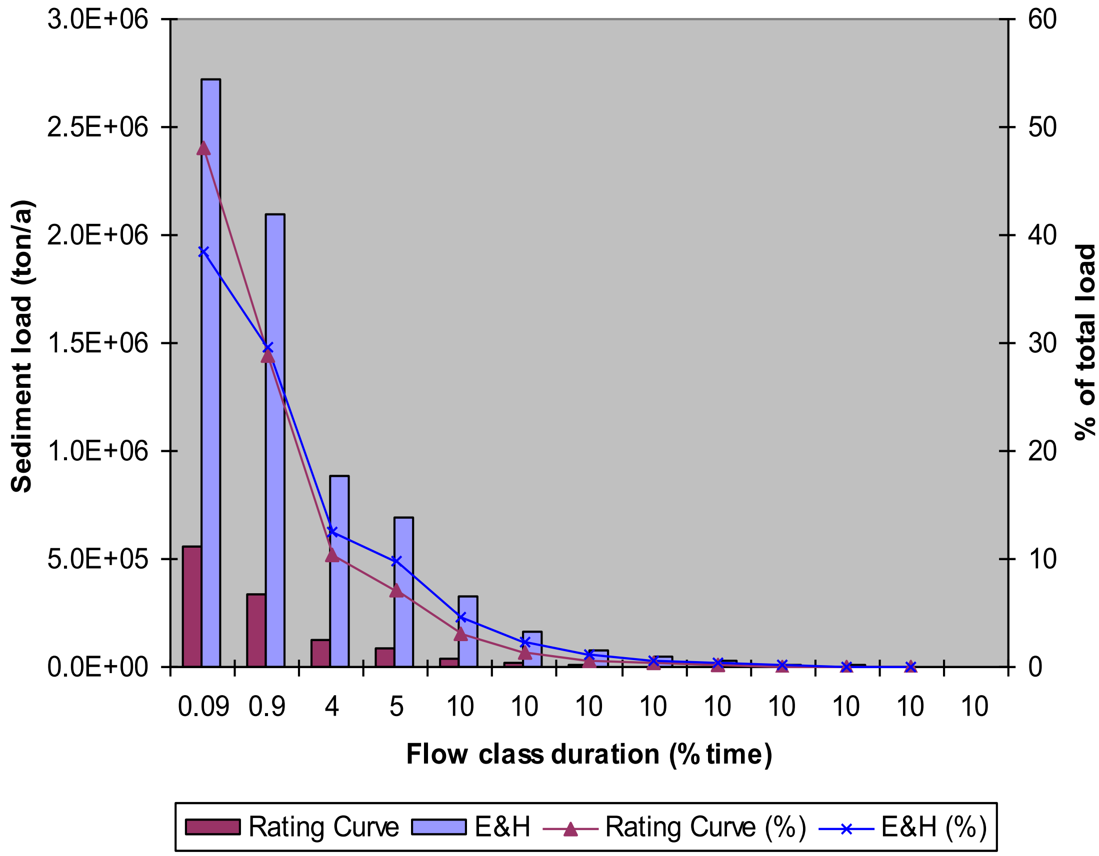


Figure 6.1-1 Sediment load distribution

From **Table 6.1.1** it can be seen that both approaches yield similar results in that the effective discharge is the discharge that is equalled or exceeded 0.01% of the time, although this is much more obvious for the sediment rating curve approach, with almost 50% of the total sediment transported by the effective discharge. The mean flow for that flow class represents a 1:10-year discharge for the Pongola River at that site (see **Table 6.1.2**). This is contrary to the general opinion that the effective discharge generally occurs more frequently, usually in the 5% to 0.01% flow duration class (Dollar *et al.*, 2000).

Table 6.1.1 Flow classes and associated sediment transport

		Rating curve		E&H*	
% time equalled or exceeded	Mean flow (m^3/s)	Sediment load (*1000 ton/a)	% of total load	Sediment load (*1000 ton/a)	% of total load
99.99					
90	2	0.09	0.004	1.8	0.02
80	5	0.34	0.015	5.7	0.05
70	7	0.87	0.04	13.0	0.12
60	10	1.82	0.08	24.6	0.23
50	14	3.57	0.2	44.4	0.42
40	19	6.99	0.3	79.9	0.8
30	29	16.07	0.7	165.4	1.6
20	41	35.27	1.6	328.7	3.1
10	62	82.86	3.7	693.5	6.5
5	103	120.51	5.4	881.7	8.3
1	185	334.84	15.0	2093.8	19.7
0.1	475	559.35	25.0	2716.5	25.5
0.01	1914	1071.20	48.0	3585.4	33.7
	Σ	2233.8	Σ	10634.4	

*Engelund and Hansen's sediment transport formula

Table 6.1.2 Pongola flood peaks

Recurrence interval (years)	Flood peak (m^3/s)
2	800
5	1400
10	1900
20	4600
50	10500

The one significant problem with the outlined approach, is the determination of the different flow classes. Choosing different intervals could yield different results. Also all the flow classes should really have the same duration to be able to compare the contribution of each flow class. Another aspect of that problem is the fact that all flows equalled or exceeded less than 0.01% of the time are not included in the evaluation. It may be argued that these flows do not occur frequently enough to be effective, but as can be seen in **Table 6.1.3**, this is not the case. Another flow class was added, representing the discharges equalled or exceeded between 0.01% and 0.001% of the time. The flow duration is very short, and yet these flows manage to transport more than 35% of the total sediment load.

Table 6.1.3 Extended flow classes and associated sediment transport

		Rating Curve			E&H*	
% time equalled or exceeded	$\overline{Q}$ (m^3/s)	Sediment load (ton/a)	% of total load	Cumulative %	Sediment load (ton/a)	% of total load
99.99						
90	2	0.1	0.002	0.00	1.8	0.01
80	5	0.3	0.01	0.01	5.7	0.04
70	7	0.9	0.02	0.03	13.0	0.08
60	10	1.8	0.05	0.08	24.6	0.15
50	14	3.6	0.09	0.17	44.4	0.27
40	19	7.0	0.2	0.4	79.9	0.5
30	29	16.1	0.4	0.8	165.4	1.0
20	41	35.3	0.9	1.7	328.7	2.0
10	62	82.9	2.2	3.9	693.5	4.2
5	103	120.5	3.1	7.0	881.7	5.4
1	185	334.8	8.7	15.7	2093.8	12.8
0.1	475	559.3	14.6	30.3	2716.5	16.6
0.01	1914	1071.2	27.9	58.2	3585.4	21.9
0.001	10541	1605.0	41.8	100	5772.2	35.2
	Σ	3838.7		Σ	16406.6	

***Engelund and Hansen's sediment transport formula**

From **Table 6.1.3** it can also be seen that all flows greater than 50 m^3/s are significant, accounting for 98% of the total sediment load.

The concept of an effective discharge can be very useful when determining a flow regime that will maintain a river in its natural or equilibrium state. However, the method outlined above still holds some problems, such as the determination of the flow duration intervals and the exclusion of the less frequently occurring floods.

6.2 Proposed Guidelines to Determine and Limit the Impact of Dams on the Downstream River Morphology

Mathematical modelling should be used to investigate the changes in the sediment balance and sediment load-discharge relationship between pre-and post-dam conditions.

The following methodology is proposed:

- Delineate the study area in terms of the morphological processes.
- Determine the reference condition and present geomorphological state, using:
  - Historical aerial photos and surveys.
  - Investigate possible changes in sediment yield.
- Describe the morphological processes of the river, including sediment transport, based on flow patterns, sediment characteristics (field work) and the downstream boundary conditions.
- Establish a sediment load–discharge relationship from observed suspended sediment concentration data considering seasonal trends and sediment transport capacity, which might limit the concentration.
- Use the sediment load–discharge relationship with the observed flow record to determine the catchment sediment yield, taking into account trapping of sediment by existing upstream dams.
- Compare this sediment yield with observed or estimated mean annual values of sediment yield determined by one of the following methods:
  - Sediment load-discharge rating curves obtained from observed suspended sediment concentrations in conjunction with long-term flow records.
  - Surveys of reservoir sediment deposits.
  - Sediment yield maps.
- Should no observed suspended sediment data be available, the sediment transport capacity can be used. The sediment transport capacity and corresponding sediment loads are calculated for a long time period (> 15 years) based on observed flow data. The sediment load is integrated over the whole period and the sediment yield thus determined. The sediment transport capacity is then, if necessary, adjusted to yield the observed sediment yield.
- Generate long-term time series data of natural flow and concentration/sediment load by using the sediment load- discharge relationship.
- Simulate the natural condition with a numerical hydrodynamic and morphological model:
  - Upstream boundary – concentration (C_{in})/sediment load (Q_{sin}) and flow (Q_{in})
  - Downstream boundary – f(discharge or water level)
  - Calibrate hydrodynamic model bed roughness, based on field measurements.
- Establish the natural sediment transport processes, including erosion and deposition, in the river.
- Generate current and future scenario flows and sediment transport:
  - Reduce sediment yield (t/a) by sediment trapping in future planned upstream dams

- Use generated flows with development, or if not available, simulated new flows at the dam, by considering water use, net evaporation, full supply capacity of reservoir, etc. If the effect of more than one dam has to be investigated, or if the point of interest is far downstream of the dam, flows may have to be routed through the catchment, together with the downstream catchment flows. Abstractions downstream should be lumped to reduce total catchment flow.
- Adjust the sediment load-discharge relationship to obtain the reduced mean annual sediment yield (t/a), also considering sediment transport capacity (concentration should not be higher than the maximum observed concentration, if reliable long-term observed data is available).
- Generate time series of flows and concentration/sediment load.
- Generate time series of flows and concentration/sediment load with increased sediment yield above natural (due to changing land use).

- Simulate the sediment transport through the river with dam operated with storage or hydropower operation: evaluate deposition and erosion patterns and compare with natural conditions.
- Determine the critical conditions for re-entrainment of sediment from the riverbed and associated flood discharge, considering possible effects of cohesive sediment (sediment characteristics to be obtained from bed sediment samples and grading analysis).
- Simulate sediment transport through the river with realistic possible artificial flood releases from dam(s), considering the following:
  - Magnitude: annual up to 1:10-year flood.
  - Duration: as close as possible to natural hydrograph shape.
  - Frequency: once or twice a year, depending on the flood magnitude and availability of water.
  - Timing: together with a large enough natural runoff event and at the beginning of the rainy season (for the greatest effectiveness).

  Use future development scenario flows with floods added, after comparison with natural runoff record.
- Recommend IFR/EFR flood peaks, frequency and duration.

In addition to the clear water artificial flood releases, sluicing through and/or flushing of sediment from the reservoir can be considered at relatively small reservoirs where excess water is available.

6.2.1 Passing High Sediment Loads Through the Reservoir

Sluicing:
When the storage capacity-mean annual runoff (MAR) ratios of reservoirs in the world are plotted against the capacity-sediment yield ratio, the data plot as shown in Figure 6.2.1 (Basson and Rooseboom, 1997). Most dams have a capacity-MAR ratio of between 0.2 to 3, and a life of 50 to 2000 years when considering reservoir sedimentation.

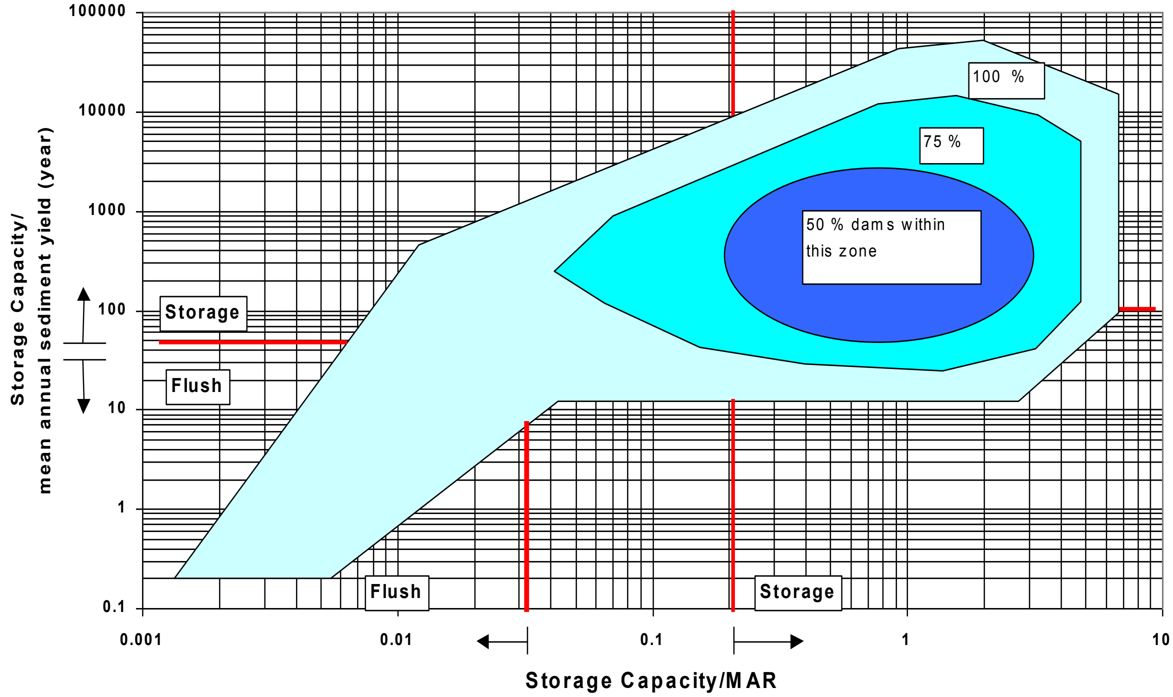


Figure 6.2-1 Universal reservoir classification system in terms of storage, runoff and sediment yield

When the capacity-MAR ratio is less than 0.03, sediment sluicing or flushing should be carried out during floods and through large bottom outlets, preferably with free outflow conditions. Flushing is a sustainable operation and a long-term equilibrium storage capacity would be reached. When capacity-MAR ratios are however larger than 0.2, not enough excess water is available for flushing.

Successful sluicing depends on the availability of excess water and relatively large bottom outlets at the dam. First Falls and Second Falls on the Mtata River, South Africa, have been operated in series with sluicing through two large bottom radial gates at each dam. After about 20 years of operation the reservoir storage capacity remains more than 70 percent of the original capacity. For successful flushing the reservoir capacity-mean annual runoff ratio should be quite small, say less than 0.05 year. Free outflow conditions are preferable, but not a requirement like with flushing, and only partial water level drawdown is required as long as the sediment transport capacity through the reservoir is high during a flood.

6.2.2 Removal of Sediment

Flood Flushing:
Flushing can be a very effective way to remove accumulated sediment deposits from a reservoir. As with sluicing, excess water is required with large low-level outlets capable of passing the say 1:5 year flood under free outflow conditions. Successful flood flushing is carried out at Phalaborwa Barrage on the Olifants River where 22 large, 12 m wide radial gates were installed, covering the whole width of the river (Figure 6.2.2). The reservoir has been operated since the 1960s, and maintains a long-term capacity in the order of 40 % of the original capacity.

At other reservoirs the flushing is less effective for example the case of Welbedacht Dam, South Africa, which has 5 large radial gates but which are not located at the river bed but 15 m above it. After 20 years of operation, 85 percent capacity was lost and today only about 9 million m³ storage capacity remains and this is with regular flushing during floods above 400 m³/s. The flushing duration is limited to about 10 hours, the period of time during which water purification to the city of Bloemfontein can be temporarily stopped. During 1994, 3 million m³ sediment was flushed out during two floods with total flushing duration of 20 hours. The storage capacity is however still decreasing.

Figure 6.2-2 Phalaborwa Barrage flood flushing

Planning, design and judicious operation of water resources are of key importance in limiting the impacts of reservoir sedimentation. In small reservoirs as much as 40% of the original capacity can be maintained in the long-term by regular flushing of sediments. As long as the flushing discharge sediment concentrations do not exceed the maximum values recorded at the dam site before dam construction, based on an observed sediment load-discharge rating curve, the river morphology should experience similar conditions as under natural conditions.

7. Economical model: Reservoir Conservation & Life cycle approach sustainable management of large hydro projects: the Rescon approach

7.1 Introduction

Reservoir sedimentation is a serious worldwide problem leading to loss of valuable storage; estimated at 35 km^3 to 70 km^3 per year, with a replacement cost of US$10 billion to US$20 billion annually (Palmieri et al. 2003). It is clear that a need for sustainable management of water resource infrastructure exists. Non-sustainable management of water resource infrastructure burdens future generations with the cost of decommissioning, while they are unable to share in the benefits of these facilities. Sustainable management of surface water reservoirs facilitates intergenerational equity, allowing society, in general, to benefit from developed infrastructure in perpetuity. The RESCON (REServoir CONservation) approach (Palmieri et al. 2003) has been developed by the World Bank to facilitate decision making on how to manage reservoirs in a sustainable manner at policy and pre-feasibility level. This method is discussed in what follows, supported by case studies of the Three Gorges and Sanmanxia Reservoirs.

7.2 Design life and life cycle management approaches

There is a marked difference between the conventional design life approach that pays scant attention to sustainability and the recommended life cycle management approach that focuses on sustainability. By neglecting considerations that will lead to sustainable use of the infrastructure the design life approach ignores intergenerational equity. The latter essentially implies that the current generation uses resources in a consumptive manner, leaving the problems of dealing with its remains to future generations without providing resources to do so. A more just approach is to manage developed resources in a sustainable manner so that future generations can also enjoy its benefits. A schematic comparing the design life and the life cycle management approaches is presented in Figure 1.

7.2.1 Design Life Approach

The design life approach (on the left side in Figure 1) is essentially viewed as a linear process of finite duration. Once it has been decided how long the design life would be, say 75 or 100 years, the project is planned, designed, constructed, operated and maintained for that period of time. Input of societal and environmental concerns is limited to the initial project conception stage (denoted by the thin dashed arrows) and the input occurs only once, regardless of the changes over the course of the project life. Conventionally the economic evaluation of projects does not account for the cost of decommissioning. It is assumed that such costs will be borne by future generations, without any action by present generations to make allowance to provide for such needs. This has been the practice on most, if not all, projects that have been conceived in the past. Residual concerns, such as reservoir sedimentation are depicted as external effects in Figure 1. Complete loss of storage due to sedimentation renders projects useless, without any design provisions to deal with it. The "lives" of such projects are finite, without any provision to deal with the problem.

7.2.2 Life Cycle Management

The life cycle management approach contains many of the same elements as the design life approach, but arranged in a circular fashion. This indicates perpetual use of the infrastructure in a sustainable manner. Consequently, the opportunity exists to incorporate changing environmental and societal concerns that are often associated with direct impacts of a dam (indicated by the solid arrows). Operation and maintenance, as well as sediment management, are conducted in a manner that will encourage sustainable use of the infrastructure.

Figure 1 emphasizes that the eventual decommissioning of a facility, should it be necessary, is included within the life cycle project management objectives. Inclusion of this possible activity requires consideration of the impacts of decommissioning on project life cycle economics and intergenerational equity. Should studies indicate that a particular facility cannot technically be operated in a manner that will ensure its use into perpetuity; the economic assessment requires that funding be provided by the original constructor of the facility that can be used by future generations to decommission the facility when required. By making provision for such a fund intergenerational equity is created.

7.2.3 Comparison

Principal difference between the two approaches is that the design life approach is linear and the life cycle management approach is circular. In the design life approach no allowance is made for the care of the dam and reservoir at the end of its "life", with residual safety, social and environmental concerns remaining. These are passed on to future generations without providing funding.

On the other hand, the life cycle management approach, with its circular progression, is principally aimed at continued, indefinite use of the facility, fully taking account of the potential need for decommissioning. However, decommissioning is only an option that is considered if no other management options for perpetual use are available. By fully taking account of the potential need from decommissioning as one of the management options, this approach allows for creation of a sinking fund that will provide monetary resources to future generations for this purpose.

7.3 Implementation

Implementation of the life cycle management approach is facilitated by making use of the RESCON (REServoir CONservation) methodology and computer program described by Palmieri et al. (2003). The

RESCON approach is intended for use in initial decision making, at policy or feasibility level. When applying it to policy level decision making it would be implemented as a review of the owner's portfolio of dams and reservoirs. The tools can be used to decide whether it is economically feasible to manage the reservoirs and dams in a sustainable manner and account for intergenerational equity. In the case of government dam owners this is obviously a very important concern as government is the custodian of society's assets and is reasonably expected to take account of intergenerational equity.

Application of the RESCON methodology to conduct feasibility studies of dams and reservoirs facilitates identification of the most economical design approach while concurrently recognizing short, medium and long term needs, evaluating the feasibility of sustainable management of the infrastructure, and recognizing the responsibility towards intergenerational equity.

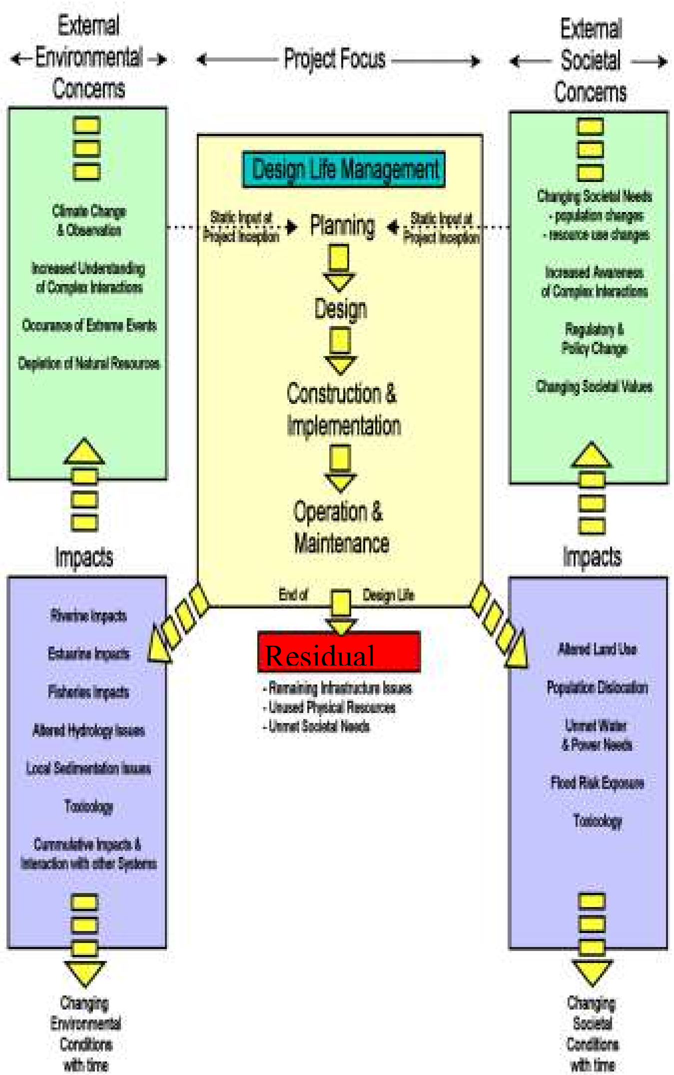
RESCON can also be applied to existing dams and reservoirs to assess the desirability of sustainable management and determine what kind of modifications are required, if any, to accomplish this. The alternative to sustainable management is to allow the reservoir(s) to silt up and implement decommissioning procedures at the end of their physical life. Should the latter choice be identified as the only feasible alternative, a sinking fund that will pay for the decommissioning should be established to ensure intergenerational equity. The intent of the sinking fund is to not burden future generations with the cost of decommissioning, while earlier generations are the sole beneficiaries of the benefits of the infrastructure.

The RESCON approach consists of three principal elements, which include determination of:

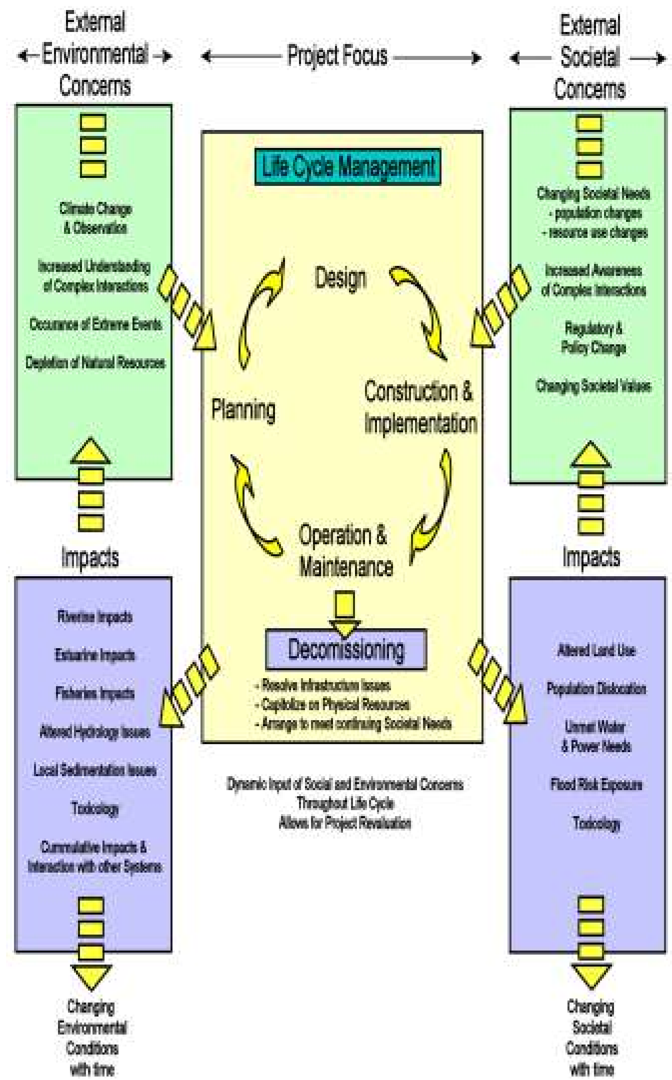
- Technical feasibility of reservoir sedimentation management
- Economic feasibility of reservoir sedimentation management
- Assessment of environmental and social aspects of optional management techniques.

7.3.1 Technical Feasibility

Techniques that have been successfully applied to manage reservoir sedimentation in the past are summarized in Figure 7.3.1-1. This figure categorizes management approaches according to location, i.e. upstream of the reservoir, within the reservoir, at the dam and downstream. The techniques that can be applied downstream of the reservoir are not aimed at reducing the volume of deposited sediment in a reservoir, but are directed at managing the environmental aspects of sediment that might be discharged downstream of the facility. The other approaches are specifically aimed at reducing the volume of deposited sediment in the reservoir.



External Environmental Concerns
Project Focus
External Societal Concerns
Design Life Management
Climate Change & Observation
Increased Understanding of Complex Interactions
Occurance of Extreme Events
Depletion of Natural Resources
Static Input at Project Inception
Planning
Static Input at Project Inception
Changing Societal Needs
- population changes
- resource use changes
Increased Awareness of Complex Interactions
Regulatory & Policy Change
Changing Societal Values
Design
Construction & Implementation
Operation & Maintenance
Impacts
Impacts
End of
Design Life
Residual
- Remaining Infrastructure Issues
- Unused Physical Resources
- Unmet Societal Needs
Riverine Impacts
Estuarine Impacts
Fisheries Impacts
Altered Hydrology Issues
Local Sedimentation Issues
Toxicology
Cummulative Impacts & Interaction with other Systems
Altered Land Use
Population Dislocation
Unmet Water & Power Needs
Flood Risk Exposure
Toxicology
Changing Environmental Conditions with time
Changing Societal Conditions with time



External Environmental Concerns
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Increased Awareness of Complex Interactions
Regulatory & Policy Change
Changing Societal Values
Impacts
Impacts
Decomissioning
- Resolve Infrastructure Issues
- Capitolize on Physical Resources
- Arrange to meet continuing Societal Needs
Riverine Impacts
Estuarine Impacts
Fisheries Impacts
Altered Hydrology Issues
Local Sedimentation Issues
Toxicology
Cummulative Impacts & Interaction with other Systems
Altered Land Use
Population Dislocation
Unmet Water & Power Needs
Flood Risk Exposure
Toxicology
Dynamic Input of Social and Environmental Concerns Throughout Life Cycle Allows for Project Revaluation
Changing Environmental Conditions with time
Changing Societal Conditions with time

Figure7.3-1 Comparison of the design life and life cycle management approaches

Detail of optional sediment management strategies are discussed in publications like Palmieri et al. (2003), with the most comprehensive recording of state-of-the-art experience and expertise found in Morris and Fan (1997). RESCON assesses the technical feasibility of optional sediment management strategies at pre-feasibility / policy level. Once the feasible techniques for managing reservoir sedimentation have been identified by the RESCON program, their economic feasibility is determined in order to identify the most economical approach.

7.3.2 Economic Feasibility

Conventional economic analysis of large water resource projects is based on a benefit/cost approach that uses the Net Present Value (NPV) of the benefits and costs over the "design life" of the project to calculate the benefit/cost ratio. These analyses usually do not account for dam decommissioning at the end of the life of the facility, and it is rare for sediment management considerations to be included as part of the assessment. It is often argued that the NPV of the cost of decommissioning that will take place 75 or 100 years into the future is very small and that omitting its consideration would not materially affect a decision. This approach is flawed.

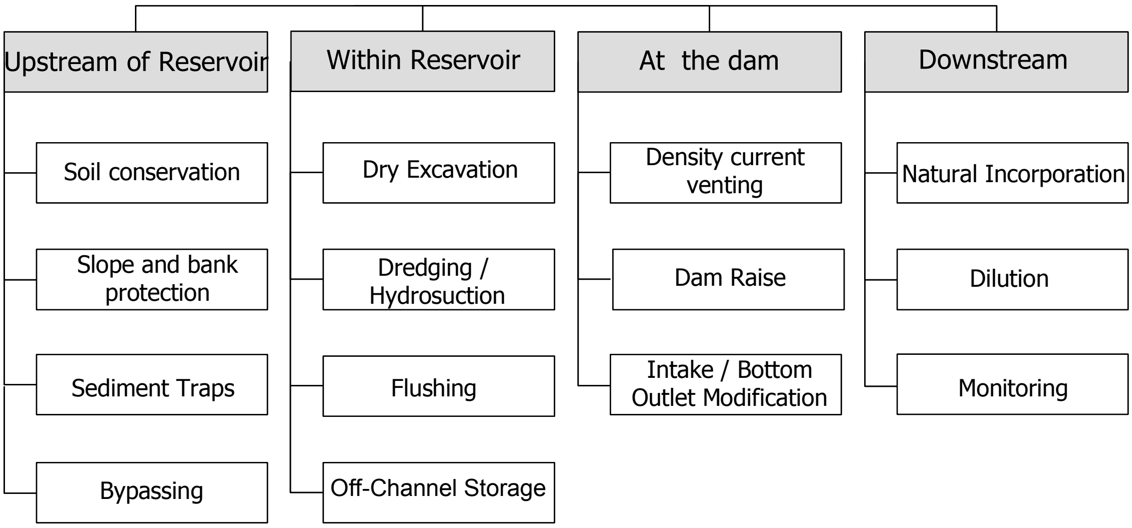


Figure 7.3-2. Sediment management approaches that could be used to facilitate sustainable us of reservoirs

The approach that is followed in RESCON methodology is to account for all the major benefits and costs over the complete life cycle of a project and, in particular, to acknowledge the need for intergenerational equity. The most favorable management option is then identified by making use of optimal control theory to maximize the algebraic sum of net benefits, capital cost and salvage value (Palmieri, et al. 2003), i.e.

$$Maximize \sum_{t=0}^{T} NB_t \cdot d^t - C2 + V \cdot d^T$$

subject to

$$S_{t+1} = S_t - M + X_t$$

given the initial capacity S_0 and other physical and technical constraints. The symbols used in the formulation are defined as: NB_t = Net benefit in year t; d = discount rate factor defined as 1/(1+r), where r = discount rate; C2 = initial capital cost of construction (=0 for existing facilities); V = salvage value; T = terminal year; S_t = remaining reservoir capacity (volume) in year t; M = trapped annual incoming sediment; X_t = sediment removed in year t.

In the case of reservoirs the salvage value *V* is usually negative as it represents the cost of decommissioning at the terminal time T, should this prove the most economical solution. In such a case allowance for intergenerational equity is made by establishing a sinking fund that will create a large enough retirement fund to decommission the facility. The annual investment (*k*) into the sinking fund is calculated as,

$$k = -m \cdot V / ((1 + r)^T - 1)$$

where m = interest rate (which can differ from the discount rate r).

When assessing the economic feasibility of a decommissioning option, the amount *k* is subtracted from the net benefits on an annual basis.

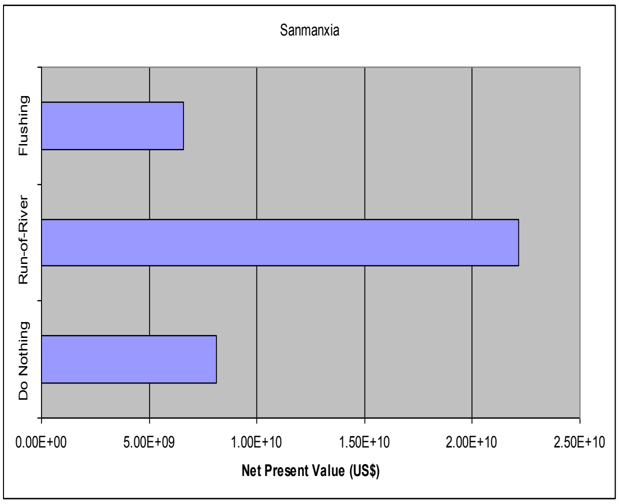
7.3.3 Environmental and Social Safeguards

When assessing a project at policy or pre-feasibility level it is often not justified to conduct a full-blown environmental impact assessment, although the need for evaluating the environmental and social impacts of various courses of action exists. Preliminary consideration of the potential environmental and social impacts of alternative courses of action is allowed for in the RESCON approach by making use of an Environmental and Social Safeguard approach. Six safeguards have been identified by the World Bank for use in preliminary assessment of projects. These include as assessment of the impact on natural habitat, impacts on human uses of the impacted natural resources, the need for resettlement, impacts on cultural assets, impacts on local communities and trans-boundary effects. A rating system to estimate the collective impact of a proposed course of action has been developed which provides guidance as to the relative magnitude of environmental and social impacts (Palmieri et al. 2003).

7.4 Case studies

Case studies have been performed in Morocco and Sri Lanka during the course of development of the RESCON approach (Palmieri 2003). In all cases the findings indicated that sustainable management, by implementing appropriate reservoir sedimentation management techniques, is always the most economic approach. In preparation for this paper the authors conducted additional studies on the Sanmanxia and Three Gorges Reservoirs, which are reported herewith. Space limitations prevent us from providing detailed information. We therefore only provide a summary of the results of the investigation.

The analyses indicated that flushing is technically feasible for both reservoirs, which has already been proven to work at Sanmanxia Dam and Reservoir (Morris and Fan 1998) and has been concluded to be feasible at Three Gorges Dam and Reservoir, following extensive study. Due to the size of these facilities, sediment flushing and density current venting are the only techniques that can be considered for maintaining reservoir capacity in the long term. Other options, like for example dredging or dry excavation are not technically feasible.



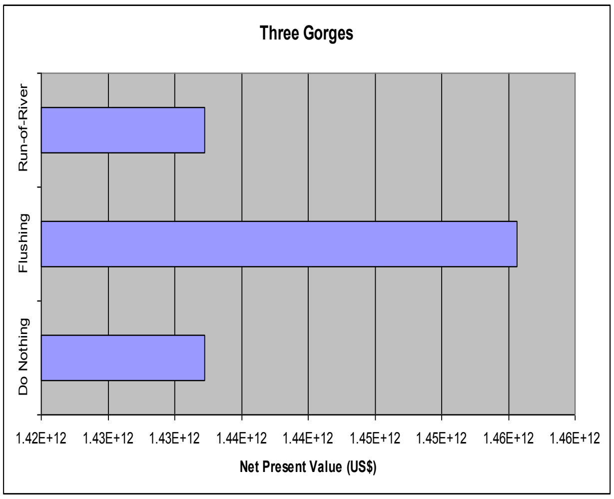


Figure 7.4-1 RESCON economic optimization results for Sanmanxia and Three Gorges.

The RESCON economic optimization indicates that flushing is the most optimal solution for Three Gorges Dam, but not for Sanmanxia Dam (Figure 3). The three options that are potentially feasible in both the cases are flushing, and the run-of-river and "do nothing" options. What is meant by "run-of-river" in the RESCON approach is that the reservoir is allowed to silt up completely during the course of its life and is from there onwards operated in a run-of-river fashion to generate hydroelectric power. In the case of Sanmanxia Dam the economic optimization indicates that the latter is the most economic solution, with flushing and the "do-nothing" approaches almost on par in second place. In the case of Three Gorges Dam, the economic optimization indicates that flushing is, by far, the most economic management approach, with the run-of-river and "do-nothing" options less desirable.

These results most probably reflect the fact that Three Gorges Dam was designed with sustainable management of the infrastructure in mind right from the beginning, while Sanmanxia Dam was originally designed using "design life" principles. Although Sanmanxia Dam has subsequently been modified to allow flushing and density current venting, it comes at a cost as implied in the RESCON economic analysis. The advanced design of Three Gorges Dam is testimony of the foresight of its designers who designed a facility that can be used in perpetuity. This is the first very large hydroelectric facility in the world that has been designed and built, and will be managed by using "life cycle management" concepts as its basis.

7.5 Summary

This chapter summarizes the RESCON approach developed by the World Bank that can be used at pre-feasibility and policy making level to make decisions pertaining to the most economic and technically feasible approaches for sustainable management of water resource infrastructure. The economic optimization uses optimal control theory to select the most desired approach that is technically feasible for managing surface water reservoirs. A unique characteristic of this approach is that it fully recognizes the value of intergenerational equity. Case studies performed in Morocco and Sri Lanka, and for the Chinese Sanmanxia and Three Gorges Reservoirs indicate that it is almost always the optimal economic solution to manage reservoirs in a sustainable manner.

The conventional design life approach that has been used in the past to design water resource infrastructure is incomplete and flawed, does not allow for intergenerational equity and results in a number of unresolved residual issues when a reservoir silts up. The life cycle management approach to water resource infrastructure management is not only technically feasible but also economically optimal, while concurrently leading to intergenerational equity and sustainable use of the infrastructure in perpetuity.

8. Conclusions & Recommendations

This bulletin investigated the current global state of reservoir sedimentation. The findings in this bulletin show that the sedimentation rate was:

For countries with recorded data	=	0.96 %/ year;
Predicted average sedimentation rate	=	0.8 %/ year;
Predicted weighted average sedimentation rate	=	0.7 %/ year;

The first value is simply the average sedimentation rate for the countries that data was collected from. The second value is comprised of the countries with recorded data incorporated with the predicted values, for the remainder of the countries, and is just a numerical average. Finally, the third value is average of the predicted and recorded data weighted by the storage capacity of each country.

The current total large dam reservoir storage capacity for the world is 6100 km^3. In 2006 the storage capacity left free of sediment was 4100 km^3 which means a build up of sediment of 2000 km^3 (33 %), which, if left unchecked could potentially increase to a volume of sediment of 3900 km^3 by the year 2050 (based on current storage capacity). This means that by 2050 roughly 64 % of the world's current reservoir storage capacity could be filled with sediment.

Hydropower dams make up 81.5 % of the world's total current storage capacity and are typically only affected by sediment when more than 80 % of the total storage capacity is lost, while for non-hydropower dams the yield is seriously affected when 70 % of the total storage is lost.

Countries that could experience critical sedimentation volumes by year 2050 are: Afghanistan, Albania, Algeria, Bolivia, Botswana, China, Columbia, Ecuador, France, Fiji, Iran, Iraq, Jamaica, Kenya, Libya, Malaysia, F.Y.R.O. Macedonia, Morocco, Mexico, Namibia, New Zealand, Oman, Pakistan, Puerto Rico, Saudi Arabia, Singapore, Sri Lanka, Sudan, Tanzania, Tunisia and Uzbekistan. Almost one third of these countries are in Africa.

A number of aspects currently limit the life of reservoirs during the planning, design and operational phases of new dams:

- Management options such as sluicing, flushing and density current venting are seldom considered in great detail, since storage operation is assumed to be the only mode of operation, even as the reservoir ages. This will hopefully change with the reconsideration of salvage value of dams to achieve sustainability and inter-generational equity.
- Although detailed physical and computational model studies of the reservoir operations and sedimentation processes are carried out during the design phase, the transfer of knowledge and implementation of operational procedures to limit sedimentation is often poor.
- Sedimentation studies considering non-storage operated management options are often not linked to the firm water yield analysis of the river-reservoir system. This will help tremendously in the optimization of reservoir sluicing/flushing operation and optimization with hydropower generation.
- Reservoir sedimentation management options do not consider the impacts on the river downstream of the dam in great enough detail during planning and design phases. This should be done using hydrodynamic-fluvial morphological computational modelling, considering the possible flood attenuation by the reservoir, sediment discharges at the dam, tributary inflows and sediment loads, in the long-term over a period of at least 20 years. Social and ecological aspects should also be addressed.

The Bulletin discusses possible downstream ecological impacts of a dam related to the fluvial morphology and possible mitigation measures are discussed.

An economical model is also presented in this Bulletin, the RESCON approach (Palmieri et al. 2003), for determining the technical and economic feasibility of sustainable management of reservoirs by using Sanmanxia and Three Gorges reservoirs as case studies. Practical experience when applying the RESCON (REServoir CONservation) approach indicates that it is almost always more economical to manage reservoirs in a sustainable manner by implementing sound reservoir sedimentation management strategies. Conceptually RESCON uses the "life-cycle management" approach instead of the "design life" approach frequented by conventional design, operation and maintenance of water resource infrastructure.

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